On the Assessment of the CO_2 Emissions from the Industrial Sector: the Role of Energy and Exergy Analysis Methods, an Approach to Enhance Sustainable Strategies

BY

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Sur l'évaluation des émissions de CO_2 du secteur industriel; le rôle des méthodes d'analyse d'énergie et d'exergie, une approche pour renforcer les stratégies durables

Raul ARANGO MIRANDA

RÉSUMÉ

La croissance démographique, l'urbanisation rapide et les progrès technologiques ont entraîné une augmentation de la demande en énergie. Au cours des 50 dernières années, les sociétés du monde entier se sont transformées de manière plus rapide et incessante. La croissance de la population a entraîné la génération de mégapoles; parallèlement, la croissance économique de ces régions entraîne une grande consommation de biens. Cela défi la disponibilité des ressources naturelles ; en conséquence, la relation de l'unité industrielle avec son environnement urbain a été modifiée dans le but de créer le moins d'impact possible sur le paysage.

L'augmentation de la population, du PIB et des exportations au cours des dernières décennies a entraîné la croissance de l'industrie manufacturière et du transport de marchandises. Globalement, le secteur industriel reste l'un des trois principaux consommateurs de combustibles fossiles; par conséquent, il s'agit de l'une des principales sources de gaz à effet de serre (GES), entraînant des problèmes pour l'environnement et la santé. En Amérique du Nord en particulier, le secteur industriel représente environ 50% de la consommation totale d'énergie et plus de 30% des émissions totales de dioxyde de carbone (CO_2).

Une définition simple de l'exergie affirme que l'exergie est l'énergie disponible pour être utilisée. Les applications antérieures d'exergy comprennent la comptabilité des ressources, les économies d'énergie, l'analyse de systèmes complexes et l'amélioration de l'efficacité.

L'objectif général de cette recherche était de valider l'utilité de l'analyse exergétique en tant qu'outil permettant d'aider les décideurs à concevoir des politiques énergétiques et environnementales futures, tant au sein d'institutions publiques que privées, en vue de renforcer les stratégies durables. Pour explorer la pertinence de l'exergy, une approche géographique a été appliquée pour analyser trois niveaux géographiques différents (global, régional et local). Par la suite,, analysez les principaux facteurs d'émissions de CO2, dans le cadre des hypothèses relatives à la courbe de Kuznets dans l'environnement (EKC), y compris les indicateurs d'exergie.

Afin d'examiner la pertinence de l'analyse des exergies, nous avons introduit de nouveaux indicateurs des émissions de CO_2 (consommation d'énergie-exergy et efficacité énergétique-exergétique), ainsi que des indicateurs établis des émissions de CO_2 (produit intérieur brut, intensité énergétique, intensité carbonique, ouverture commerciale et l'index du développement humain) pour étudier leur pertinence en tant qu'indicateurs.

Nous avons utilisé ces travaux de recherche pour formuler des recommandations sur la manière d'appliquer l'analyse exergétique à grande échelle (secteurs de la société) et de fournir les outils nécessaires pour effectuer une analyse exergétique à l'aide de ces données, afin de mieux s'appliquer à ce secteur industriel particulier.

A l'échelle global, les résultats montrent une forte corrélation entre le CO_2, le PIB, la consommation d'énergie, l'intensité énergétique et l'ouverture commerciale est observée, d'autre part, des valeurs statistiquement non significatives concernant l'ouverture des marchés et l'intensité énergétique. À l'échelle régionale, la causalité de Granger a été trouvée dans les variables d'exergie proposées aux États-Unis et au Mexique; L'ouverture commerciale a également montré une causalité au Canada et aux États-Unis. Finalement, au niveau local, le secteur industriel mexicain est encore peu efficace en termes d'efficacité exergétique, par rapport aux pays développés.

Les résultats de l'approche méthodologique appliquée menée pour les trois niveaux géographiques proposés dans la thèse confirment l'adéquation des méthodes exergy en tant qu'outil d'aide à la conception de politiques énergétiques et environnementales, aussi bien au sein d'institutions publiques que de sociétés privées, en tant qu'approche visant à améliorer las stratégies durables. En particulier pour les décideurs des trois pays de l'ALENA l'exergie s'avère utile en raison de l'impasse actuelle des négociations, non seulement pour lutter contre les émissions de CO_2, mais aussi pour promouvoir la croissance de la part des énergies renouvelables. L'ajout de l'indicateur exergétique fournit un aperçu intéressant des stratégies énergétiques et environnementales. Cette thèse a montré la nécessité d'accélérer les processus de décarbonatation; il a été démontré que la méthode d'analyse d'exergie offre une approche non traditionnelle du droit de réduire les émissions de gaz à effet de serre et contribue à le développement durable.

Mots-clés: analysés d'exergie, analysés d'énergie, secteur industriel, émissions du CO_2, soutenabilité, courbe du Kuznets, politique énergétique, politique environnemental.

On the assessment of the CO_2 emissions from the industrial sector: the role of energy and exergy analysis methods, an approach to enhance sustainable strategies

Raul ARANGO MIRANDA

ABSTRACT

Growing population, rapid urbanization and technological advancements have resulted in increasing energy demand. During the last 50 years, societies around the world have been transforming in a faster and incessant way. The growth of the population has resulted in the generation of mega-cities; at the same time, the economic growth of these areas entails consumption of goods. It is challenging the availability of natural resources; as a result, the relationship of the industrial unit with its urban environment has been changing in the pursuit to create the minimum possible impacts to the landscape.

This constant increase in population, gross domestic product and exports in the last decades has resulted in the growth of the manufacturing industry and the transportation of goods. Globally, the industrial sector remains as one of the three main consumers of fossil fuels; hence, it is one of the prime sources of greenhouse gases (GHG), resulting on environmental and health problems. Particularly in the North American region, the industrial sector embodies about 50% of the total energy consumption and more than 30% of the total carbon dioxide (CO_2) emissions.

A simple definition of exergy affirms that exergy is the energy that is available to be used. Some applications of exergy include resource accounting, energy conservations, complex systems analysis and efficiency improvements. The general objective of this research was to validate the suitability of exergy analysis, as a tool to assist decision makers in the design for future energy and environmental policy, both in public and private institutions as an approach to enhance sustainable strategies. To explore the appropriateness of this indicator, a geographical approach was applied to analyze three different geographic levels (global, regional and local). Additionally, analyze the main drivers of CO_2 emissions, within the framework of the environmental Kuznets curve (EKC) hypotheses, including exergy indicators.

In order to explore the appropriateness of exergy analysis, new indicators of CO_2 emissions (energy-exergy consumption and energy-exergy efficiencies) were introduced, with the goal to be compared to traditional indicators of CO_2 emissions (gross domestic product, energy intensity, carbon intensity, trade openness and human development index) to study their suitability as indicators.

Results of these thesis gives recommendations on how to apply exergy analysis on a large scale level (societal sectors) and to provide the tools necessary for exergy analysis, using this data, so as to better be applicable to this particular industrial sector. At global level, the results shows high correlation between CO_2, GDP, energy consumption, energy intensity and trade openness; but not statistically significant values for trade openness and energy intensity. At regional level, granger Causality was found from proposed exergy variables in the USA and Mexico to CO_2 emissions; also causality was detected in Canada and the US from trade openness to CO_2 emissions. Finally, at the local level (study case), poor exergy efficiency is still occurring in the Mexican industrial sector, compared with developed countries.

The outcomes of the applied methodological approach conducted for the three geographical levels proposed in the thesis, confirms the suitability of exergy methods as a tool to assist the design of energy and environmental policy, both in public institutions or private corporations as an approach to enhance sustainable strategies. Particularly, for policymakers of the three NAFTA countries, exergy proves value due the current impasse of negotiations, not only for tackling CO_2 emissions, but also for promoting growth in the renewable energy share. The addition of the exergetic indicator provides an interesting insight on energetic and environmental strategies. This thesis showed the need to speed de-carbonization processes; it was demonstrated that the exergy analysis method provides a non-traditional approach in the right to reduce GHGs and contribute to sustainable development.

Keywords: exergy analysis, energy analysis, industrial sector, CO_2 emissions, sustainability, Kuznets curve, energy policy, environmental policy.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF ABREVIATIONS

C int	Carbon intensity
CC	Climate change
CO_2	Carbon dioxide emissions
ED	Environmental degradation
Ef	Exergy of fuels
EG	Economic growth
EKC	Environmental Kuznets Curve
En int	Energy Intensity
EnC	Energy consumption
EnvCAN	Environment and Climate Change Canada
Ex con	Exergy consumption
Ex int	Exergy intensity
ExC	Exergy consumption
$Exergy^{Ch}$	Chemical exergy of the system under study
$Exergy^{Kn}$	Kinetic exergy of the system under study
$Exergy^{Ph}$	Physical exergy of the system under study
$Exergy^{Pt}$	Potential exergy of the system under study
$Exergy_{sys}$	Exergy of the system under study
$ffCO_2$	Carbon dioxide emissions from fossil fuels
ffEncon	Energy consumption from fossil fuels
GDP	Gross domestic product
GHG	Green House Gases

GW	Global warming
HHV_f	High heating value of fuels
IEA	International Energy Agency
OECD	The Organization for Economic Co-operation and Development
$pcCO_2$	Carbon dioxide emissions per capita
pcGDP	Gross domestic product (GDP) per capita; USD 2005
pcTPES	Total primary energy supply per capita
PCF	Product carbon footprints
RED	Renewable energy directive
SEMARNAT	Secretaria de Medio Ambiente y Recursos Naturales, México
Tropn	Trade openness
UN	The United Nations
UNIDO	The United Nations Industrial Development Organization
USEPA	The United States Environmental Protection Agency
WB	World Bank
γ_f	Exergy grade function
NAFTA	The North American Free Trade Agreement
IEA	The International Energy Agency

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

GJ/t	giga joules per tonne
GWh	giga watt hour
kg	kilogram
kj	kilojoules
Mton	million tonnes
$MtCO_2$-eq	million tonnes of carbon dioxide-equivalent
Mtoe	million tonnes of oil-equivalent
MWh	megawatt-hour
PJ	petajoule
Atm	pressure (atmospheres)
C	temperature (degree Celsius)
K	temperature (degree Kelvin)
USD	United States dollar
yr	year

INTRODUCTION

Growing population, rapid urbanization and technological advancements have resulted in increasing energy demand. Modern societies require huge amounts of products and services, the consumption rates are constantly increasing, putting pressure in natural resource consumption, with undesired decline in forest and agricultural lands, solid waste generation, pollution of water basins and air pollutants. Growing consumption trends of citizens increase the pressure on the industry to satisfy such demands. Globally, the industrial sector remains as one of the main consumers of energy, mostly from fossil fuels, particularly the heavy industry. In 2016, total global gas emissions continued to increase by about (+/- 1%) to about 49.3 gigatonnes in CO_2 equivalent (Gt CO_2 equiv). Most of the emissions (about 72%) consist of CO_2 (Jos GJ Olivier, Schure, & Peters, 2017).

Since early 70's, first versions of environmental laws were focused to detect, control and minimize the harm caused by pollutants. To combat these negative effects, after the Rio Conference in 1992 (Keating, 1994), new comprehensive and preventive approaches were developed to support the theory of sustainable development, such as the life cycle assessment, industrial ecology, industrial symbiosis, etc.

In December 1997, while meeting in Kyoto, Japan, for the 3rd Conference of Climate Change, representatives from 160 countries were developing specific climate protection objectives and the options available to achieve them.

A key point to better inform decision makers, at governmental or private level is the proper use of energy policies and the development of environmental regulations. An essential part of the use of energy is the application of energy analyses in the industrial sector. Among Gong and others (Gong & Wall, 2001, 2016; Hammond & Stapleton, 2001), Scholars agree that exergy analyses are a great fit to complement energy analysis with the goal to enhance the performance of industrial processes. So far, it is mainly used as a complement to the energy concept, to describe, analyze and improve energy systems and processes (Gong & Wall, 2001). Reistad (G. M. Reistad, 1975) acquainted one the first definitions of exergy:

> *"Availability or exergy is defined as the thermodynamic property that measures the potential of a system to do work when restricted by the inevitable surroundings at To, Po, (dead state temperature and pressure)."*

Recently (BoroumandJazi, Rismanchi, & Saidur, 2013), defines exergy as:

> *"The maximum amount of work that can be produced by a system or a flow of matter or energy in equilibrium with its surroundings"*

For the purposes of this thesis, when referring to exergy, the definition of BoroumanJazi will be considered. Exergy can be used to detect inefficiencies of a process by locating the degradation of energy. Mandatory regulatory instruments, as exergy analysis, are tools that address sectorial-level greenhouse-gas emissions; they include, i.e. EU's Renewable Energy directive (RED), etc. A growing number of public and private voluntary product carbon footprints (PCF) schemes are also being applied (J. F. Peters, Petrakopoulou, & Dufour, 2014).

Also, this thesis applies the Environmental Kuznets Curve (EKC) hypothesis, since it is the most influential model for relating CO_2 emissions to economic development to answer an important question in environmental economics: must economic development come at the expense of environmental degradation, or is there some tendency for pollution to fall after the economy achieves a certain level of income?

In this context, the general objective of this work is validate the suitability of exergy (an environmental accounting method belonging to the energy analysis approach, to assist energy and environmental practitioners and research efforts for future policies and regulations at governmental institutions and private firms. The thesis is composed of five chapters described below.

Chapter 1

Present the review of the literature used as a theoretical and practical basis for the development of the work, summarizing a background of the main concepts, methodologies and ensemble approaches in energy and exergy analysis methodologies, similarly the environmental concepts of the environmental Kuznets curve and sustainability.

Chapter 2

Introduce the concept of exergy and the exergy analysis methodology, also the approach of the environmental Kuznets curve (EKC) is applied to study co-relationships between carbon dioxide (CO_2), GDP and energy consumption using panel data estimation techniques in a set of 10 countries (developed and developing) during the period 1971-2014. The results could help to analyze, compare and improve energy and environmental directives and policies for practitioners. This article was published in the journal Energies, Oct 2018 (MDPI editions).(R. Arango-Miranda, R. Hausler, R. Romero-López, M. Glaus, & S. Ibarra-Zavaleta, 2018a) Arango-Miranda, R., Hausler, R., Romero-López, *Carbon dioxide emissions, energy consumption and economic growth: A comparative empirical study of selected developed and developing countries. The role of exergy*. *Energies*, *11*(10), 2668. Preliminary data and results reported in this article were presented at the 2017 INNOVATIONMATCHMX International Congress; May 31 to June 2, 2017, in Mexico City, Mexico.

Chapter 3

Shows the research results in the article entitled: "*Economic growth, energy and the environmental Kuznets curve in North American Countries (NAFTA partners)*". It is focused to study the correlations at regional level; the variables of trade openness and exergetic renewable share are proposed to detect the main drivers of CO_2. An analysis is proposed to study corelationship between carbon dioxide (CO_2), GDP and energy consumption using panel data estimation techniques in the North American region including Canada, Mexico & the U.S.A. The hypothesis of the environmental Kuznets curve (EKC) is tested and then confirmed. The results are proposed as tools for practitioners and legislators for future energy and environmental directives and policies. Preliminary data and results reported in this article were presented at the 2016 INOVATIONMATCH MX, International Congress; April 6 to 8, 2016, in Guadalajara, Jal., Mexico.

Chapter 4

Shows the research results in the article entitled *"An Overview of Energy and Exergy Analysis to the Industrial Sector, a Contribution to Sustainability".* A study case in the Mexican Industrial Sector is developed. Exergy analysis is proposed and lifted to study the Mexican industrial sector as a study case. The results support the need to employ exergy analysis to complement the prevailing energy-based methods utilized to develop official reports or environmental and energetic policies and strategies, once it was demonstrated that exergy provides key elements to improve the energetic performance. This work was published in the journal Sustainability (MDPI Editions), Jan 2018. Arango-Miranda, R., Hausler, R., Romero-López, R. (2018). An overview of energy and exergy analysis to the industrial sector, a contribution to sustainability. *Sustainability*, *10*(1), 153. Preliminary data and results reported in this article were presented at the 2016 INNOVATIONMATCHMX International Congress; April 5 to 8, 2016, in Guadalajara, Jal. Mexico. A similar methodology was applied to study the industrial sector of Quebec, Canada. Results of this work will be presented as an oral presentation at the ACFAS 87^{e} International Congress, 2019 edition, in Ottawa, Canada, May 27-31, 2019.

Chapter 5

Summarizes all the work accomplished in this thesis, linking the outcomes in the different chapters, while highlighting their benefits and limitations. Presents theoretical and operational implications arising from the results and findings obtained during the development of the work, as well as the main considerations for future research venues.

In this work, the study of the main drivers of CO_2 emissions is based on the detection of the correlation between them, for which statistical analysis, particularly the theory of the Kuznets environmental curve (EKC), was applied. These theories establish different data compilation criteria over time. Also, the selection of variables included economic, social, environmental and exergetic indicators. In Chapter 2, at global geographic level, a sample of ten was studied in a period of 44 years. In Chapter 3, at regional geographic level, a sample of three countries was selected for a period of 15 years. In Chapter 4, at local geographic level, a study case is presented including the analysis of the Mexican industrial sector (MIS).

CHAPTER 1

LITERATURE REVIEW

1.1 Atmospheric pollution and sustainability

The biggest challenge of sustainability is to achieve society-economy-environment balance, once the world population increase, urban areas grow to be able to accommodate people, demanding jobs, consumer goods and services. Consequently the request for finished products grows constantly and thus the need for greater quantity and diversity of products to fulfil such needs (United Nations Human Settlements Programme, 2010). Conversely, unsustainable lifestyles or unsustainable consumption of societies play a key challenge to reach sustainable development.

Since the latter part of the 18th century, humans have been altering the Earth at an unprecedented and unsustainable rate and scale by radical consumption rates. According with Hoekstra, assessing land, water, energy, material, and other footprints along supply chains is paramount in understanding the sustainability, efficiency, and equity of resource use from the perspective of producers, consumers, and government (Hoekstra & Wiedmann, 2014).

In developed countries, even environmentally minded and environmentally active people often consume far beyond their fair share of global emissions (Lenzen & Cummins, 2011). In an era of social media, this consumption trends has been rapidly widespread. These impacts are related to the structure as well as the level of consumption (Thøgersen, 2014) and has implications on energy and environmental policy.

Nowadays, more than half the world's population lives in urban areas, thus, it is predicted that by the year 2050, most of the geographic regions will be predominantly urban (see Figure 1-1).

Growing population, urbanization always growing and technological advancements have resulted in increasing energy demand. Disproportionate population growth over the last 70 years is associated with the development of mega-cities.

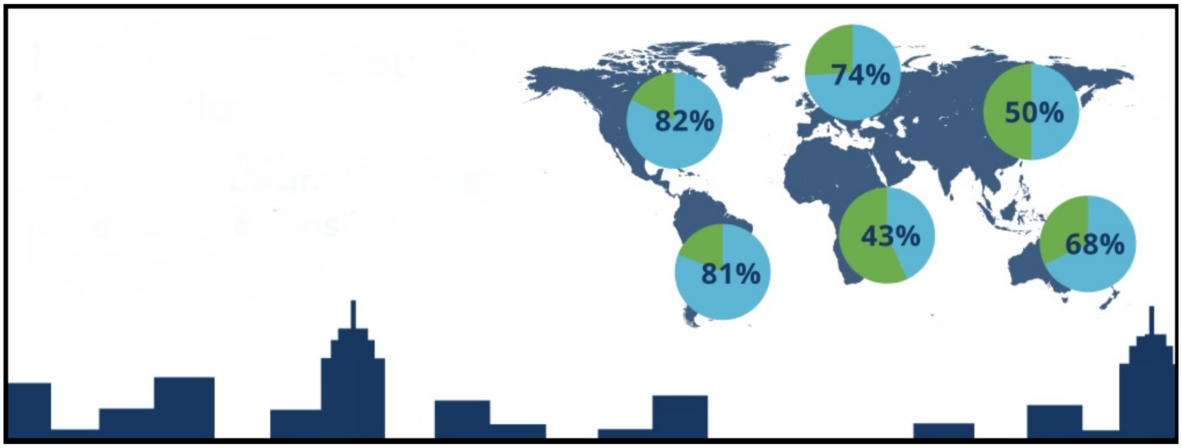

Figure 1-1 Urbanization around the world. Adapted from UN (I. Nations, 2018)

1.2 Industrial sector environmental assessment

Consumption of fossil fuels as the main source of energy is triggering environmental degradation. Particularly, large emissions of green-house gases (GHG) associated with urban regions are leading to unsustainable societies. CO_2 emissions are the most important GHG, by 2016 reaches near 72% of the total amounts of GHG (Jos GJ Olivier et al., 2017). Anthropogenic CO_2 from the burning of fossil fuels are the primary cause of global warming (Davis & Caldeira, 2010).

The industrial sector faces the challenge to meet this high demand for manufacturing goods and simultaneously, optimize resources and reduce impacts of its activities. Figure 1-2, describes a list of the countries with the largest ecological footprint globally. The mega-cities will multiply globally, compromising key natural reserve areas; therefore, the new industrial challenge is to mimic nature to be able to remain inside or close to the urban region and fill up with the demands required by future societies (Susan, 2017; United Nations Industrial Development Organization (UNIDO), 1997), avoiding long travel distances to omit the increase of CO_2 emissions by transport materials, products and workers.

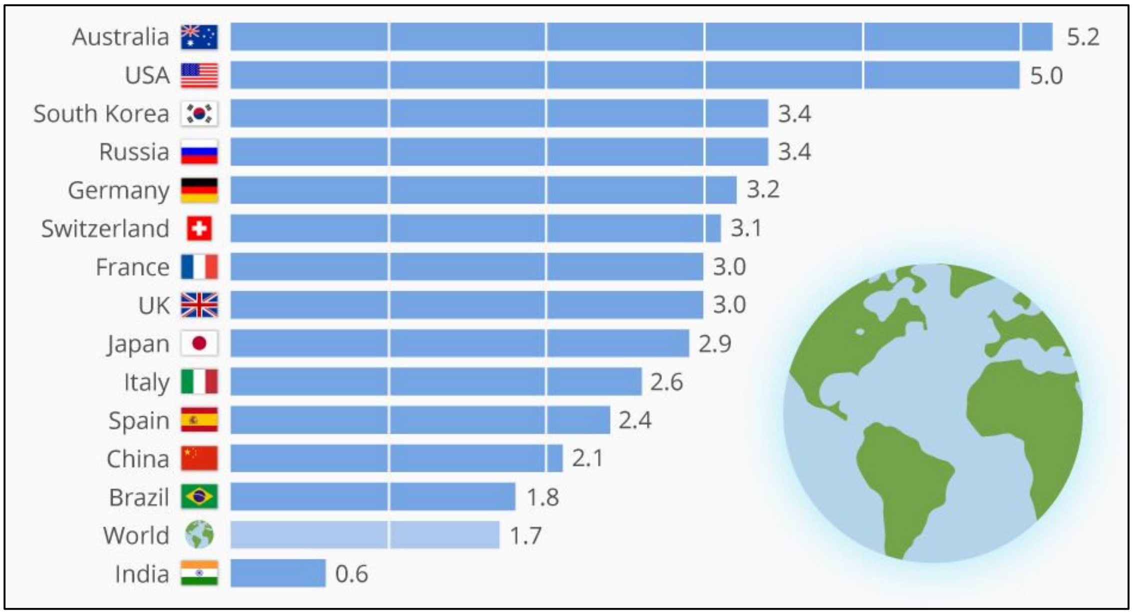

Figure 1-2 Countries with the largest ecological footprint and the number of earths needed to satisfy their consumption lifestyles.
From Statista, infographics. (Dyfed Loesche, 2017)

Paradoxically, while industrial activities mean benefits for human development in the form of consumer goods and services, these products came with by-products, and environmental pollutants (air emissions, solid wastes, wastewater, etc.), due industrial process's inefficiencies (United Nations Human Settlements Programme, 2013). Many changes in environmental laws have been occurring since recent decades, subsequently new comprehensive and preventive trends to support the theory of sustainable development were created aimed to mimic natural ecosystems to consume and discard as little as possible and still obtain consumer goods (US-Environmental protection Agency (US-EPA), 2016).

In 2012, Loiseau (Loiseau, Junqua, Roux, & Bellon-Maurel, 2012) developed a comparison of nine different methods of environmental assessment of territories (Figure 1-3), establishing the strengths and weakness or limitations of some of them concluding that there is presently no consensual and widely adopted method although it is recommended for example, by European directives.

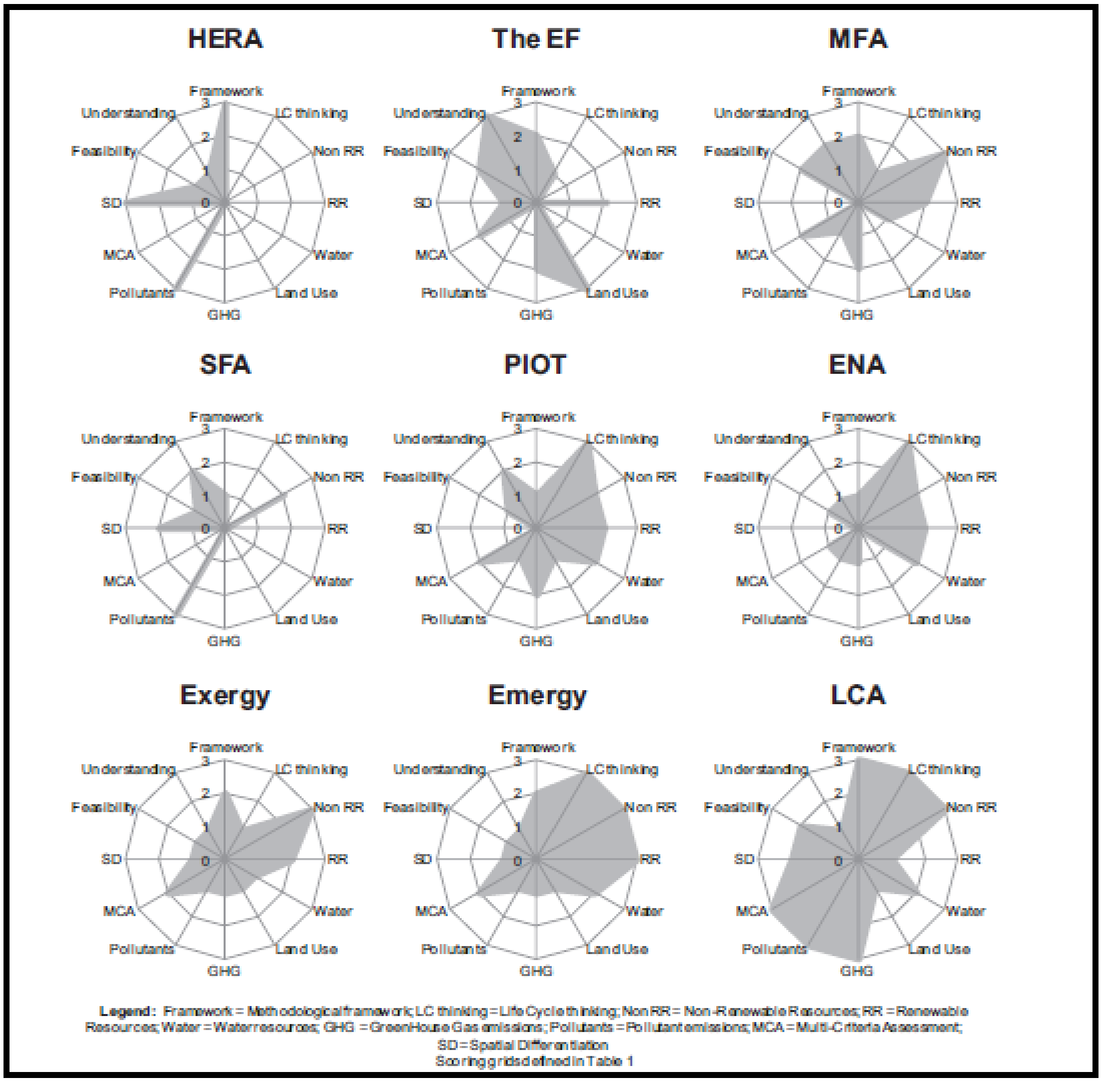

Figure 1-3 Comparison of environmental assessment tools. From Loiseua, 2013. Human and environmental risk assessment (HERA); The ecological footprint (EF); Material and energy flow analysis (MFA); Substance flow analysis (SFA); Physical input- output table (PIOT); Ecological network analysis (ENA); Exergy; Emergy; Life cycle assessment (LCA)

Among others, exergy analysis and emergy synthesis are part of the energy family methods applied in the environmental assessment of territories and natural or anthropogenic systems. Compared to material and energy flow analysis applies (tools based on the first law of thermodynamics), exergy analysis applies the principles of the second law of thermodynamics.

According to (Gasparatos & Scolobig, 2012), after 25 years of debate there is no shortage of sustainability assessment tools. He claims that sustainability assessment tools can be divided into three broad categories: monetary, biophysical and indicator-based. Exergy, emergy, ecological footprint material and energy flow analysis are part of the biophysical category.

Hence, these conventional methodologies are applied in the assessment of industrial environmental impacts. Governmental institutions were created, with the goal to apply the law enforcement, some examples are: Environment Canada (EC), the Environmental Protection Agency of the United States (US-EPA) or the European Environmental Agency (EEA), among others. They have been evolving according to the challenges faced throughout time. Due their global effects and time persistence, industrial atmospheric pollutants represent a major concern of global warming, particularly the emissions of CO_2. Kyoto's protocol, established the commitment of countries to reduce greenhouse gases emissions. GHG's are relevant because the most of it has fossil fuels as the main source since the Industrial Revolution; the switch to renewable sources is changing panorama, but it is a mid-term solution (Loiseau et al., 2012). Figure 1-4 describes the growing trend curves of CO_2 emissions by geographic region, since 1971 to 2015 (International Energy, 2017).

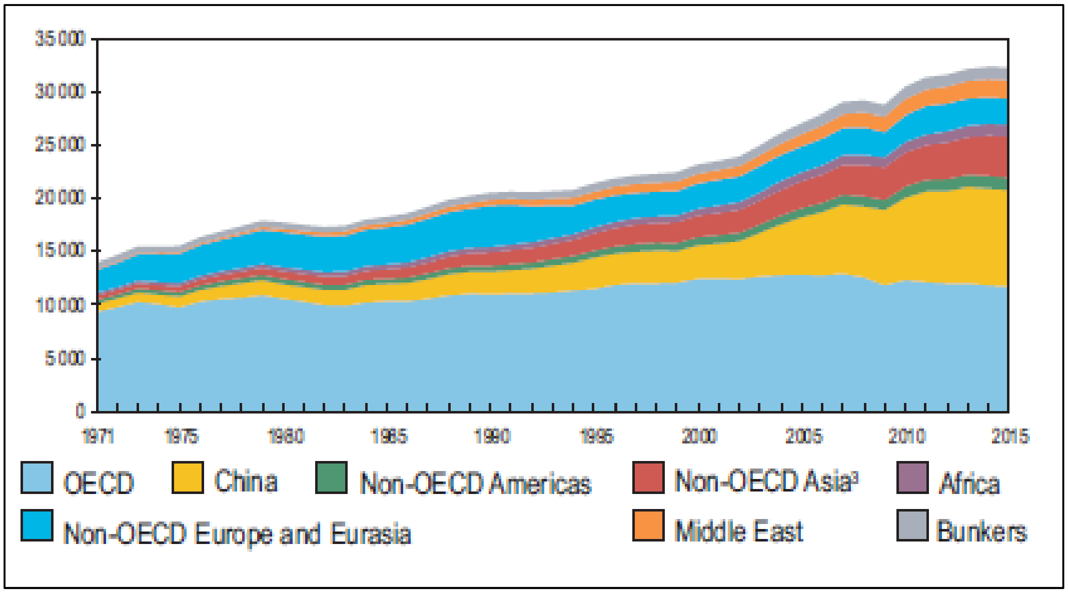

Figure 1-4 CO_2 emissions (Mt) by geographic. From IEA, 2017

1.2.1 Principles of air pollution emissions assessment; greenhouse gases (GHG) and Carbon dioxide (CO_2)

The relationship between energy consumption and economic growth has received a great deal of attention in the recent past. This is principally because of the enormous implications that this relationship has for policy prescriptions relative to energy conservation. Moreover, environmental concerns require more attention around the globe with a lot of calls to reduce green-house gases (GHG) emissions which are seen as a major source of global warming (Appiah, 2018).

Climate change (CC) has become a topical issue across the world. Scientist places it at the top of the list of problems that humans need to deal with in current times and future times. There is also a consensus that human (anthropogenic) activities are causing recent global warming (Intergovernmental Panel on Climate Change (IPCC) UNEP, 2016). Climate change is also a disaster that human beings must cope with for decades. Excessive amounts of GHG's (water, vapors, carbon dioxide, methane, nitrous dioxide and chlorofluorocarbons) in the atmosphere are the main reason for global climate change (Özokcu & Özdemir, 2017).

According to the US-EPA (US-Environmental protection Agency (US-EPA), 2016), greenhouse gas can be defined as any gas that absorbs infrared radiation in the atmosphere . The increase of greenhouse gases emissions is a major threat to the environment of the world. The rapid economic growth and expansion of the process of industrialization of developing countries impel intensive use of energy and other natural resources as a result more residues and wastes are being released in nature that could lead to environmental degradation (Sharif Hossain, 2011).

The consumption of energy is a standard to gauge the pace of economic progress and the promotion of industrialization in developed and developing countries. But the rising demand for non-renewable energy sources in developing countries is causing negative impacts on the environment (Hanif, 2017b).

Despite efforts to improve energy efficiency, today the industrial sector remains as one of the main consumers of energy fuels with an average of 37 % overall, with a range of consumption varying from 30% to 70% locally (Dincer & Rosen, 2012). Figure 1-5 shows the world CO_2 emissions from fuel combustion, from years 1971 to 2015 (International Energy, 2017).

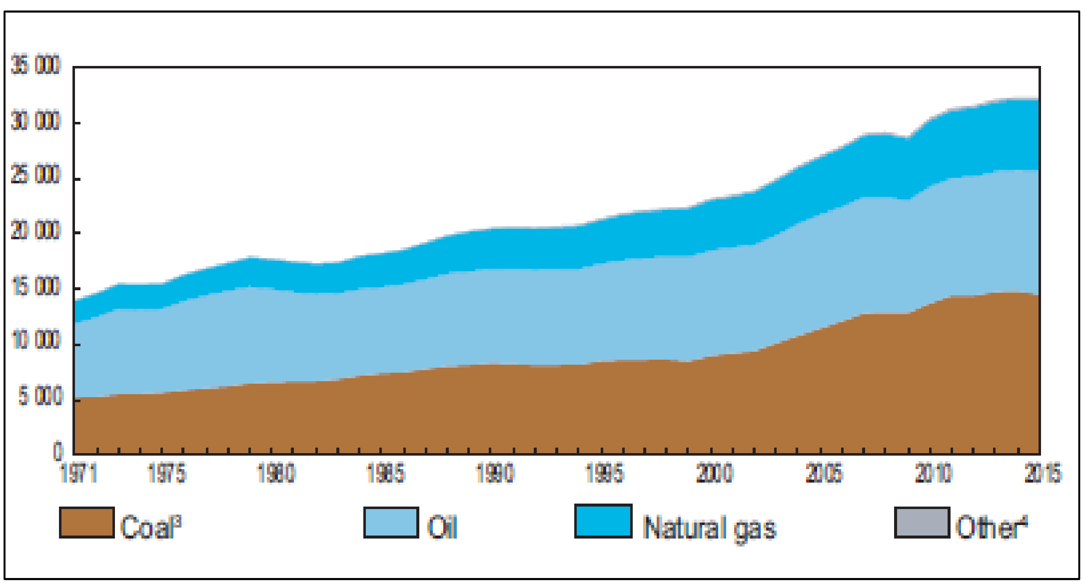

Figure 1-5 World CO_2 emissions from fuel combustion (Mt). From IEA, 2017

Therefore, the relationship between fossil fuels consumption to produce energy and to generate GHG's, requires the mitigation of source through process energetic efficiency; however this is not always realistic because several factors restrict the transformation or improvement of systems for industrial power generation, such as costs associated with production, availability of technology, design of equipment, availability of space, etc. This is a challenge proposed to the scientific community, how to evaluate and decrease the negative effects of pollutants in the atmosphere, the soil, water-bodies and ecosystems? But most important to minimize impacts on human health (Kothari, Tyagi, & Pathak, 2010).

Since the initial efforts to combat environmental harm in the 70s, constant evolution of environmental laws, codes, standards, etc., have been taken place. The command-control method used strongly during the 70s as legal tool (end of the pipe approach, failed, however promotes the creation of good environmental practices for companies worldwide (M. E. Kraft, 2011; Portney, 2010). Below, the evolution of the environmental management tools is showed in Figure 1.-6.

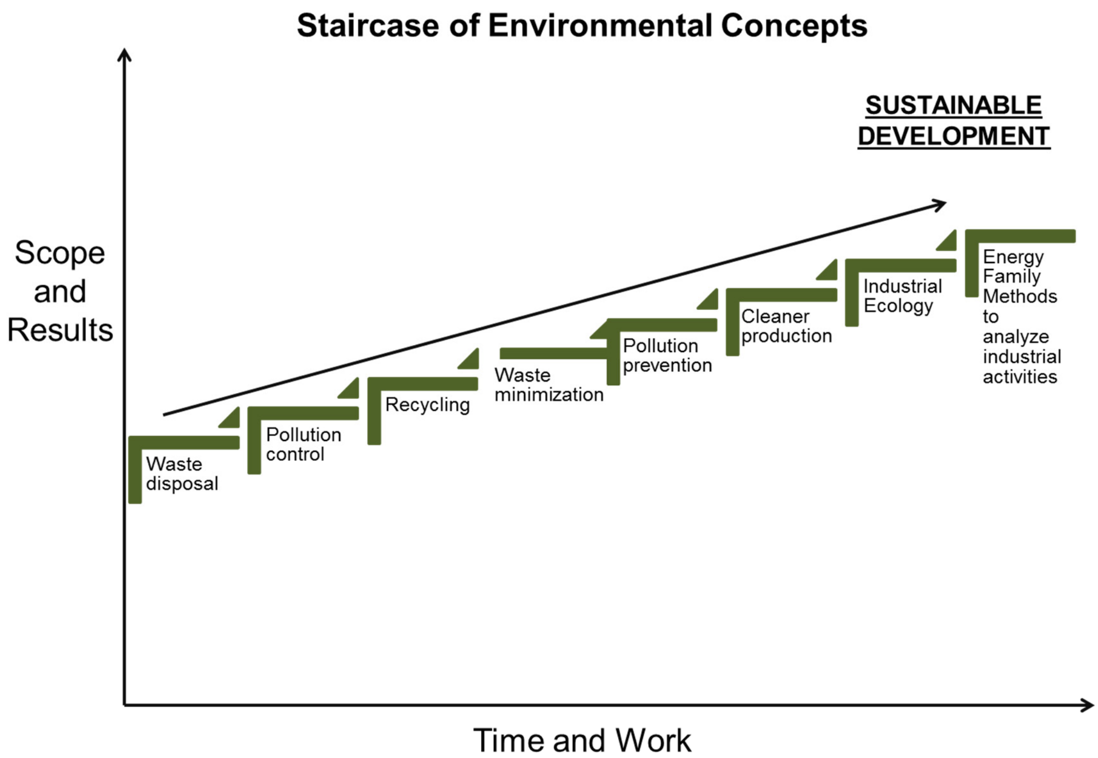

Figure 1-6 The staircase of environmental management systems.

Adapted from (Basu & van Zyl, 2006)

After decades of "command and control" environmental policy in the United States, environmental regulation and enforcement that has dictated how companies addressed environmental, health and safety issues, the amount of codes and regulations increased drastically (Richards, 1997).Consequently, the following stage of environmental tools grow up evolving in to comprehensive and management systems, from just recycling into life cycle assessment or mimic the natural ecosystems a is suggested by industrial ecology (Chertow, 2007).

1.3 Energy and exergy analysis

1.3.1 Theoretical background

On his historical review on exergy Sciubba & Wall (Enrico Sciubba & Wall, 2007), showed that exergy has been in constant evolution, with a maturity that occurred during the decade of the 70s (corresponding with the oil shock in 1973); this keystone, opened the door to further areas of research, since the development of related application of exergy for various industrial applications i.e. steam power cycles (Fiaschi & Lombardi, 2002), energy conservation (Dincer, 2002), energy conversion cycles (Dincer & Rosen, 2004), efficient energy consumption (Kotas, 2013), etc.

Meanwhile, on the field of environmental sciences, some methodologies have been developed, for example those that links costs and thermodynamics known as the Exergy Cost (Jan Szargut, David R. Morris, & Frank R. Steward, 1987). The concept of Cumulative Exergy Content (Enrico Sciubba, Bastianoni, & Tiezzi, 2008) or the Exergoeconomics or Thermo-economics (Lozano & Valero, 1987). Combined with this concept were included other externalities (Göran Wall, 1977a), bringing into new methodologies such as Exergy Life-Cycle-Assessment (Cornelissen & Hirs, 2002), or the comprehensive exergy evaluation of social systems (Göran Wall, 1987).

Regarding exergy analysis, Rosen states that it provides a more realistic basis to the system's performance, compared to energy analysis he establishes the following: "while energy analysis cannot always do that, even sometimes provides misleading information. Exergy analysis has been useful for design and performance evaluation of thermal systems during recent years.“ (Marc A Rosen, Dincer, & Kanoglu, 2008).

Although exergy and its direct connection with environmental problems does not result in a direct measurement of environmental impacts (E. Sciubba, Wall, G. , 2007). The exergy balance method allows to measure resource consumption (primary sources), to get new styles on the design of environmentally friendly industrial facilities or to redesign processes or applying reengineering tools to improve performance of old industrial plants, located mostly in developing countries. Though, regarding exergy and the environment, Rosen and Dincer have been studying this relation (Dincer & Rosen, 2004; Dincer & Rosen, 2013a; Ozcan & Dincer, 2013; Marc A. Rosen & Dincer, 2001). Their findings are focused on the influence of exergy as a tool to increase energy efficiency and simultaneously decrease environmental harm.

Scholars have been studying exergy analysis on a large-scale base, such as a country, its society or their own economic sectors (A Al-Ghandoor, 2013; Apostolos, Alexios, Georgios, Panagiotis, & George, 2013; Bühler, Nguyen, & Elmegaard, 2016; Ertesvåg, 2001; Göran Wall, Sciubba, & Naso, 1994). Figure 1-7 depicts a societal sectors structure.

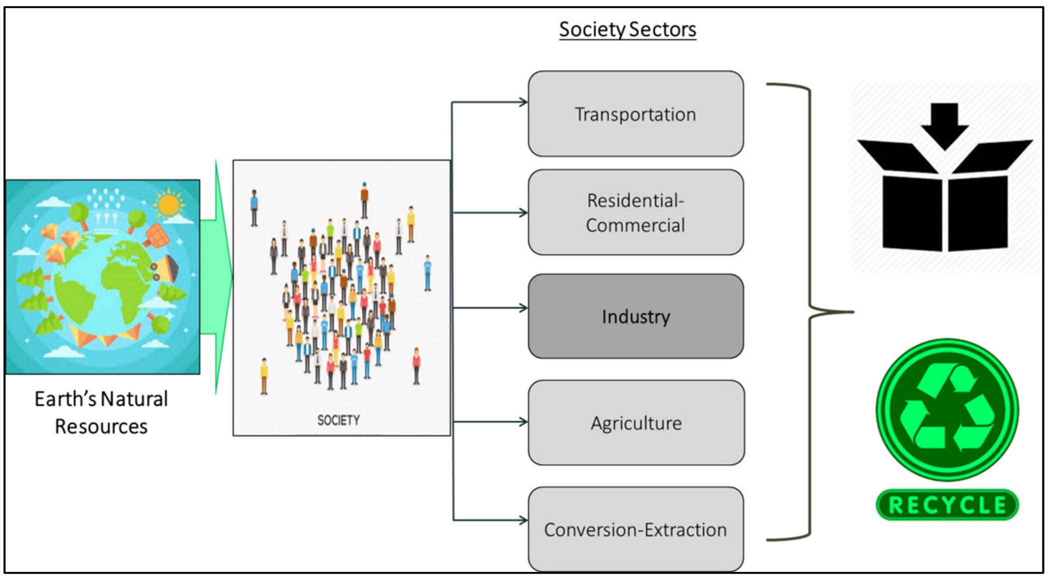

Figure 1-7 Graphical structure of society economic sectors; adapted from Utlu, 2007

Among others, recent areas of research regarding exergy, highlights those of exergy analysis in the industrial sector (Li & Tao, 2017; Wu, Wang, Pu, & Qi, 2016); on waste emissions (Mora & de Oliveira Jr, 2018; Wu et al., 2016); on processes equipment and devices (Ahmadi & Toghraie, 2016; Mehrpooya, Lazemzade, Sadaghiani, & Parishani, 2016); on renewable energy sources (Di Somma et al., 2017; Ezzat & Dincer, 2016).

1.3.2 Exergy of fuels

In 1997, Dincer (M. A. Rosen, 1992; M. A. Rosen & I. Dincer, 1997) evaluated the energy consumption of the industrial sector in Canada to increase its efficiency based on exergetic analyses. They developed one of the first large-scale exergy analysis methods. Toward the construction of an exergy balance of a non-constant flow system (like mass or energy balances), a common scenario requires establishing a control volume as well as a reference environment; it is usually established through a temperature T_0 = 25 °C and a P_0 =1 atm. (M. A. Rosen, 1992). The flow of exergy entering in a system can be best described as the sum of the totality of their exergies (physical, chemical, potential, kinetic and nuclear exergies) (Marc A. Rosen, 2013; Enrico Sciubba, 2001).

$$Exergy_{sys} = Exergy^{Ph} + Exergy^{Kn} + Exergy^{Pt} + Exergy^{Ch} + Exergy^{Nu} \qquad (1.1)$$

The chemical exergy is the maximum work that can be obtained by taking a substance having the parameters (T_o, P_o, mj_o) to the state determined by the dead state (T_o, P_o, mj_o).

The most common mass flows in industrial processes are hydrocarbon fuels at near-ambient conditions; then the terms $Exergy^{Ph}$, $Exergy^{Kn}$, $Exergy^{Pt}$, $Exergy^{Nu}$, in equation (1.1) are approximately zero; as a result, the exergy of fuels reduces only to the chemical exergy ($Exergy^{Ch}$) component.

Researchers have been proposing a correlation factor or exergy factor (A. Al-Ghandoor, Phelan, Villalobos, & Jaber, 2010; Guevara, Sousa, & Domingos, 2016; M. A. Rosen, 1992; Utlu & Hepbasli, 2007b), defined as the ratio of chemical exergy to the higher heating value (*HHVf*). With the use of these exergy factors, conversions of energy data to exergy values of energy carriers are given by proportionality constant (Bühler et al., 2016; Guevara et al., 2016). In other words, due the complexity of the chemical composition of fuels, a simple approach was applied, since the higher heating value (*HHVf*) of fuels is close to their chemical exergy component. In this work, the average exergy grade functions for different energy carriers considered were taken from several sources (Ertesvåg, 2001; G. M. Reistad, 1975; M. A. Rosen, 1992; J. Szargut, D.R. Morris, & F.R. Steward, 1987; Utlu & Hepbasli, 2007a).

1.3.3 Energy and exergy efficiency evaluation methods

With the aim to assesses the control volume, previous research applied different methods to obtain thermodynamic efficiencies (Aljundi, 2009; Dincer & Rosen, 2012; E Sciubba, 1994; Tsatsaronis, 2007). Energy and exergy heating efficiencies derives from the first and second laws of thermodynamics, respectively. Electric and fossil fuel heating processes were chosen to generate products heat at a constant temperature, either from electrical energy or fuel mass.

Due the diversity and complexity characteristics of this sector, the assessment of the accurate conditions of each process (temperature, pressure, thermodynamic properties, etc.) becomes hard to handle. However, some criterions are necessary to solve this situation. A standard method applied by Utlu (Utlu & Hepbasli, 2007b), to compute the efficiencies of electrical and fuel heating, as well for the fossil-fuel heating efficiencies has been applied in several studies for the industrial sector. Briefly, to assesses industrial activities this method consists to consider standard reference operation categories. They are divided into three main categories of temperature heating (high-medium-low) in terms of heating processes temperatures.

1.4 The Environmental Kuznets Curve (EKC)

The idea of a causal relationship between energy consumption and economic growth was first introduced in the influential paper of Kraft (J. Kraft & Kraft, 1978b), once the causality relationship between them has important policy implications. A literature review on the EKC starts with the influential research from Grossman and Krueger (Gene M Grossman & Krueger, 1995) in their attempt to explore the path of sustainable development theory to describe the environmental degradation-economic growth relationship.

The debate about what becomes first, economics or environment, no matter at local or global level was settled and the functional relationships between economic growth and environmental degradation were masterfully expressed by the environmental Kuznets curve

(EKC), an inverted U-shape curve (David I. Stern, 2004). To face the problem of GHG's as precursors of climate change is a great challenge. In the late 80's, efforts from governmental and non-governmental organizations mainly in industrialized countries, were the first steps in the route of sustainable development (Robinson, 2004).

As part of this effort to tackle greenhouse gases, CO_2 emissions are broadly used in the industry as an indicator of the environmental performance of a company (Sariannidis, Zafeiriou, Giannarakis, & Arabatzis, 2013). To control the carbon emissions issues, governments have been taking actions to face this challenge (Turki, Sauvey, & Rezg, 2018).

One way of determining the effectiveness of environmental policies is through the Environmental Kuznets Curve (EKC). The EKC hypothesis suggests that environmental damage first increases with income (GDP per capita), then declines. In other words, GDP per capita (income) and pollution per capita have an inverted U-shaped relationship (Kaika & Zervas, 2013a; Olale, Ochuodho, Lantz, & El Armali, 2018).

The environmental Kuznets curve (EKC) was initially developed by (G. M. Grossman & Krueger). At its most basic level, the EKC hypothesizes an inverted U-shape in the relationship between per capita emissions (such as CO_2) and per capita GDP (or per capita income). Relative low levels of per capita GDP, per capita emissions increase with per capita GDP but eventually at a declining rate. After per capita emissions reach a maximum, they decline as per capita GDP continues to grow (Brown & McDonough, 2016).

Several years of economic growth without bearing in mind environmental harm, scholars, practitioners and policy makers, mostly representing developed countries, perceiving the risk related with industrialization and deforestation processes, among other anthropogenic activities and react; hence, a heated debate between the importance of economy without compromising our natural resources started (Vlontzos, Niavis, & Pardalos, 2017).This dilemma about economic activity and pollution opened up grounds for a rich research agenda (Moutinho, Varum, & Madaleno, 2017).

Subsequently, researchers have been developed empirical studies of the EKC in single or multiple countries or geographical regions, applying different methodologies (Alam, Murad, Noman, & Ozturk, 2016; Ben Jebli, Ben Youssef, & Ozturk, 2016; Dinda, 2004; Panayotou, 2001).

Other researches have focused their attention on different environmental dimensions (i.e., CO_2, SO_2, NO_x, particulate matter, wastewater, protected areas) or time contexts. Mixed and even inconclusive findings are still reported (Rahman & Kashem, 2017). Scholars found that the relationship presented multiple shaped EKC such as U, inverted-U, N, etc. Additionally, there were also evidences that the testing results depended on the specific econometric models (Chowdhury & Moran, 2012). Some authors have been reviewing the vast literature of the EKC, offering an overview of the relevant past empirical studies, highlighting among others, the work of (Bo, 2011; Özokcu & Özdemir, 2017; Ozturk, 2010; David I. Stern, 2017).

Below, Table 1-1 show a brief literature review summary from some countries in search of the environmental Kuznets curve, mainly focused on the set of ten countries analyzed in this research. Table 2-1 shows the methods or tests used to determine the causality between the variables studied as well as the existence or not of the Kuznets curve. Also describes the main results, methods applied by author, year and country, taking as a sample the proposed ten countries chosen for the Global geographic scale. The criteria were to select the more relevant works in terms of newest, time frame and similar methods as those applied in our research work.

Table 1-1 Brief summary of the environmental Kuznets curve literature review

Country	Authors, year	Period	Methodology	RESULTS
Brazil	Alam, 2016	1970-2012	ARDL	**EKC Supported to Brazil** in long & short run GDP causes CO_2; Energy consumption causes CO_2
Canada	Jie He, Patrick Richard, 2010	1948-2004	Semiparametric and flexible nonlinear parametric modeling	No **EKC evidence**. CO_2 causes GDP
China	Alam, 2016	1970-2012	ARDL	**EKC supported to China** in long run GDP causes CO_2; Energy consumption causes CO_2
Italy	Magazzino, 2016	1970-2006	Granger non-causality test; Toda & Yamamoto	**No EKC evidence**; CO_2, GDP & Energy consumption are non-co-integrated. Bi-directional causality among CO_2 and GDP; also CO_2 causes energy consumption
Mexico	Gomez, 2018	1965-2014	Granger causality test; ARDL	**No EKC evidence**. **The growth hypothesis is supported.** Linear causal from total and disaggregated energy consumption to GDP.
Norway	Baek, 2015	1960-2010 (CAN, NOR, USA)	ARDL	**Little evidence of the EKC**; Energy consumption worsens the environment
S. Africa	Shahbaz, 2013	1965-2008	ARDL	**The EKC confirmed,** rise in GDP- increases energy emissions
Turkey	Soytas & Sari, 2009	1960-2000	Granger causality, Toda Yamamoto	**No EKC evidence**; CO_2 causes energy consumption
The U.K.	Sephton, 2016	1966-2013	OLS and MARS tests	**The EKC confirmed.** $pcCO_2$ causes pcGDP
The U.S.A.	Dogan, 2016	1960-2010	Co-integration, Granger causality; VECM	**No EKC evidence.** Bidirectional causality among CO_2 and GDP; CO_2 and Energy consumption; CO_2-URB; GDP-URB; GDP-TRopn.
OECD countries	Jebli, 2016	1980-2010, 25 Countries	Granger causality, short run	**The EKC confirmed.** Renewable energy and & trade have a negative impact on $pcCO_2$. Also trade openness and renewables are efficient strategies to combat global warming

CHAPTER 2

PRESENTATION OF THE RESEARCH PROJECT

2.1 Work approach: Exergy analysis for environmental policies and regulations

As environmental tool, exergy analysis methodology is a systemic and multidisciplinary approach, allowing the study of sustainability axes (economic, social and environmental topics). Also, exergy analysis is applied to detect the inefficiencies of processes by locating the degradation of energy, i.e., heat lost, etc. Scholars claim that exergy brings opportunities in decision-making to increase energy efficiency and energy conservation, e.g. (Utlu & Hepbasli, 2009).

The evolution of exergy analysis starts with the theoretical developments of Reistad, growing as a concept to resource accounting, energy conservations, efficiency improvements in industrial equipment or power cycles and its components, then including environmental applications, complex systems analysis, sectors and extended exergy analysis in societies or countries, mainly including conversion, transportation, residential and agricultural sectors. Regarding the industry, exergy analysis has been developed in three main categories: sectorial analysis, by type of industrial process; by industrial equipment.

The available evidence (Marc A Rosen, 2013) propose that compared to energy efficiencies (first law of thermodynamics), exergy efficiencies (second law of thermodynamics) offer larger areas for improvement from an exergy perspective, compared to the overly optimistic margin indicated by energy. Even even those on a large scale such as the economic sectors of a country or an entire society. Gong (Gong & Wall, 2016) established that to improve energy and material conversion processes, the exergy concept should be applied. Thus, exergy and exergy analysis are helping tools to create and preserve a sustainable or rather a vital society.

2.2 Problem statement

How can we return to pre-industrial levels of CO_2 emissions?

It is known that CO_2 occurs naturally in Earth's atmosphere, presented as a trace gas. However, there is evidence that the rate of release of carbon dioxide (CO_2) in the atmosphere may be greater than the earth's ability to assimilate it (Baldocchi & Penuelas). Anthropogenic emissions of CO_2 – primarily from use of fossil fuels and deforestation – have rapidly increased its concentration in the atmosphere. Since the Industrial Revolution, levels have almost doubled. Today are higher than at any point in at least the past 800,000 years, the concentrations reach 410 ppm, near 70% higher from pre-industrial levels of 280 ppm. The amount of carbon dioxide in the atmosphere is increasing as increased amounts of fossil fuels are burned. In 2016, Carbon dioxide emissions accounted for approximately 72% of global greenhouse gas (GHG) emissions (Jos GJ Olivier et al., 2017).

As an example, in the United States (a key player to combat climate change, highly industrialized, one the 5th most populated countries globally), the CO_2 releases to the atmosphere increased by approximately 7% between 1990 and 2013. By 2016, 22% of the total GHG emissions came from the industrial sector in the USA. This one of the reasons for which this work is focused on the CO_2 emissions from the industrial sector (International Energy, 2017).

However, despite the greater focus on CO_2 emissions and the efforts to reduce environmental damage, fossil fuels (i.e. oil, coal, fuel-oil and natural gas) still dominate overall energy consumption. Fossil fuels had an 81% share in the last 25 years. That relationship did not change between 1989 and 2014, although the use of oil fuel decreased, from 37% to 31%. During that same period, the use of natural gas increased from 19% to 21%, but most importantly the use of coal, the most pollutant of the group (due its long chains of hydrocarbons) increased from 25% to 28%, mostly in developing economies like China and India.

Industrial activities mean benefits for human development as employment, and economic development; paradoxically waste and pollutants are generated as a by-product or wastes in the form of air, solid or liquid pollutants (Portney, 2010). These problems are related to deficient planning, lack of proper environmental policies and regulations, or lack of law enforcement. The current rates of worldwide economic development show that increased energy demand at all sectoral levels may represent a threat to the achievement of global reduction objectives for 2050 (Intergovernmental Panel on Climate Change (IPCC) UNEP, 2016). The industrial sector plays a key role in terms of energy use and air emissions, particularly the high-intensity energy consumption by sub-sectors. Is it possible to use fossil fuels in a more sustainable way?

2.3 Working hypothesis

In order to analyze the correlations among CO_2 drivers to promote policy instruments, this research was split in three different geographical levels including a general set of countries, a subset and a single sample of countries.

Correlations between exergy, environmental impact and sustainability

The thesis explores the potential relationship between some industrial environmental indicators by means of the existence of the EKC; several variables are proposed, such as energy consumption, energy efficiency, with the intensity of resource utilization; the main hypothesis to test will be the existence of the EKC in the geographic levels (global, regional, local);however the statistical methods, sample of countries, time-frame set, will affect the results.

At global level, it is not expected to find the EKC; at regional level, it is expected to detect the EKC; and finally, at local level it is expected also to find the EKC.

Above all, it is expected that energy consumption would affect carbon dioxide (CO_2) emissions, at least in some of the analyzed countries, at global or regional level.

Additionally, at regional level, it is expected that exergetic variables, exergy intensity and exergetic renewable share, the higher the rates of exergetic renewable share, the lower the rates of CO_2 emissions. At local level (study case), the higher the exergy efficiencies, the lower the CO_2 emissions. To summarize, we expect correlations among exergy and environment variables.

Additionally, exergy-based indicators are proposed like exergy efficiency, exergy intensity (in both cases, higher values indicating higher resource utilization levels) and exergetic renewable share. Regarding the compute of exergy indicators, the hypothesis in this dissertation is based on the approach that, once exergy efficiency tends to increase, environmental impacts, particularly air emissions, conversely decrease, and thereafter sustainability will increase; this exergetic postulate is in accordance with Dincer (Dincer, 2002)

2.4 Objectives

Accordingly, this work explores the applicability of the exergy analysis method at large scale, specifically to widely used parameters on both, industrial sector energy as well as exergy performance. These parameters on the industrial sector include efficiency, fuel consumption, CO_2 emissions; while on the exergy performance side they include other variables related to the industrial sector and sub-sectors, like exergy consumption, exergetic renewable share, exergetic intensity. Following the traditional structure of the thesis by chapters, the research work was conducted applying a geographical level approach. We considered analysis of several countries industrial sector at global, regional and local geographic levels. A study case was proposed at local level. Thus, the following specific objectives were proposed.

Particular Objective 1

Evaluate the main drivers of CO_2 emissions with the assessment of corelationship between economic growth and energy consumption using panel data estimation techniques at global level in a set of ten countries. Additionally, propose to test the influence of an exergy variable as a determinant factor for the environmental Kuznets curve (EKC) of the selected countries (global-geographical level). At this first stage of this research the EKC will be only explored.

Particular Objective 2

Introduce and compare the suitability of exergetic variables: exergy intensity and exergetic renewable share, among others (trade openness, GDP and energy consumption) to detect the main drivers of CO_2. Also, the existence of the environmental Kuznets curve (EKC) hypothesis was studied among the North America free trade agreement (NAFTA) commercial partners: Canada, Mexico and the U.S.A. (regional-geographical level). In this second stage of this research the EKC will be applied.

Particular Objective 3

Detect the areas within the industrial sector able to improve performance and minimize impacts by exploring the energy and exergy consumption rates as well as the changes of the efficiency of energy and exergy utilization of industrial activities. Study case of the Mexican industrial sector (local-geographical level). In this third stage of this research the EKC will be applied.

2.5 Methodological framework

An approach of geographic and temporal scales was applied in this work, in three basic stages in order to fulfill the proposed objective.

Table 2-1Methodological approach

Space	**Global**	**Regional**	**Local**
Time	1971-2014	1990-2014	2000-2014
Methods	Exergy EKC (explore) Correlations IEA data bases Article 1	Exergy EKC (applying deep methods) Correlations IEA data bases Article 2	Exergy, EKC Exergy efficiency IEA data bases Article 3
Set of Countries	Ten Developing (Brazil, China, Mexico, Turkey, South Africa) Developed (Canada, Italy, Norway, The USA, The UK)	Three (The North American region) Canada, Mexico, The USA	1 (study case) Mexico

Table 2-1 above shows the characteristics used in each of the three stages referred to hereafter as Global, Regional and Local geographic levels. In general terms we can indicate that the common factor among the three stages is the exergetic analysis, detect correlations among the proposed variables, the test to detect the existence of the EKC and the generic database created for ten countries from the data published by the IEA on its website, between 1970 and 2014.

But, a difference among each of the three levels was that at first glance the EKC was only explored in the study of the set of ten countries; with the acquired experience, the next level was to apply in a deeper way econometric methods to test the EKC in a sub-set of three countries at regional level. And finally, at local level, instead to go deeper to study a single to detect the EKC, the research was focused to compute exergy efficiencies.

In the beginning we developed a matrix dataset including several variables and 10 countries; utilized to compute exergy indicators. This dataset was the main structure linking the three main parts of this thesis. The International energy agency website, was taken as main source, but complemented with countries official publications to corroborate or extend additional information. In Chapter 4, at the global geographic level, a set of ten countries was selected in a period of 44 years, from January 1971 to December 2014. The criteria applied to select the sample were based on two conditions, economic development and CO_2 emissions. As economic criteria, the selection of a mix of developed and developing economies was applied. Regarding their CO_2 emissions, the climate change performance index was considered.

Similarly, in Chapter 5, at regional geographic level, taken from the set of ten countries previously studied, a subset of three countries was selected in a shorter period of 25 years from January 1990 to December 2014, adjusted to the live-span of the NAFTA. The same data bases of IEA was applied based on the previously cited data base from the IEA. The criterion applied to select the sample was the study the economic and environmental influence on the North American countries compromising the NAFTA. Also, we applied several methodology test to determine the existence or not of the EKC

In Chapter 6, at local geographic level, a study case is applied to analyze the Mexican industrial sector (MIS); the goal was to evaluate the performance of the sector, with the use of two exergy indicators. The results of the MIS were compared with the OECD and non-OECD countries. Additionally, the correlations between the drivers of CO_2 are analyzed; due to data restrictions, the period of study was from January 2000 to December 2015.

CHAPTER 3

CARBON DIOXIDE EMISSIONS, ENERGY CONSUMPTION AND ECONOMIC GROWTH: A COMPARATIVE EMPIRICAL STUDY OF SELECTED DEVELOPED AND DEVELOPING COUNTRIES. "THE ROLE OF EXERGY"

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Abstract: Diverse factors may have an impact on carbon dioxide (CO_2) emissions; thus, three main contributors, energy consumption, gross domestic product (GDP) and an exergy indicator are examined in this work. This study explores the relationship between economic growth and energy consumption by means of the hypothesis postulated for the environmental Kuznets curve (EKC). Panel data for ten countries, from 1971 to 2014 have been studied. Despite a wide gamma of research on the EKC, the role of an exergy variable has not been tested to find the EKC; for this reason, exergy analysis is proposed. Exergy analyses were performed to propose an exergetic indicator as a control variable and a comparative empirical study is developed to study a multivariable framework with the aim to detect correlations between them. High correlation between CO_2, GDP, energy consumption, energy intensity and trade openness are observed, on the other hand, not statistically significant values for trade openness and energy intensity. The results do not support the EKC hypothesis. However exergy intensity opens the door for future research once it proves to be a useful control variable. Exergy provides opportunities to analyze and implement energy and environmental policies in these countries, with the possibility to link exergy efficiencies and the use of renewables.

3.1 Introduction

The growing consumption trends of modern societies increase the pressure on manufacturing to satisfy such demands (Lorek & Spangenberg, 2014). The growing request of fossil fuels as the main source of energy is triggering environmental degradation, that is without a doubt, one of the most pressing global atmospheric challenges experienced by developed and developing countries in the 21st century in the form of greenhouse gases (GHG), global warming (GW) and climate change (CC) (Hanif, 2017a). In this growing trend of economies, over the past few decades, countries were transitioning from agriculture to manufacturing or even service-based economies in the case of Asian countries (To & Lee, 2017). Low-carbon energy transitions are important to mitigate climate change, reduce air pollution, and reduce fossil fuel resource depletion (Urban & Nordensvärd, 2018).

Once natural resources are not infinite as a source for economic activities, then uncontrolled economic development entails actual risks for the global environment (Arrow et al., 1995). Energy is an indispensable input in the economic activity process. Since the effects of openness and economic reforms, China among other developing countries has become the fastest growing countries in the world, prompted by rapidly increasing energy consumption (Hu, Guo, Wang, Zhang, & Wang, 2015). The rates of worldwide economic development indicate that increased energy demand at all sectoral levels may represent a threat to the achievement of global reduction objectives for 2050 (Intergovernmental Panel on Climate Change (IPCC) UNEP, 2016).

Rapid global economic growth between 2005 and 2013, influenced global GHG emissions increased by 18.3% reaching more than 35 billion tons by 2013 (Environment and Climate Change Canada, 2018). According to the Inter-governmental Panel on Climate Change (IPCC), the combustion of fossil fuels unavoidably produces GHGs, comprising mainly CO_2, among others (Intergovernmental Panel on Climate Change (IPCC) UNEP, 2016). Virtually 90% of the CO_2 emissions has a fossil-fuel source and therefore are determined by the energy demand or the level of energy-intensive activity. After several periods of economic growth without considering environmental damage, academics, practitioners and policy makers, mostly representing developed countries perceiving the risk related to industrialization and deforestation processes, among other anthropogenic activities and react; hence, a heated debate between the importance of economy without compromising our natural resources started (Vlontzos et al., 2017). How to tackle the problem of climate change is a great challenge. Sustainability offers an approach to combat GHG and CC.

In late 80s, efforts from governmental and non-governmental organizations mainly in industrialized countries, were the first steps in the route of sustainable development (Robinson, 2004). To control the carbon emissions issues, governments have been taken actions to face this challenge (Turki et al., 2018). As part of this effort, in industry, the CO_2 emissions are broadly used to represent the environmental performance of a firm (Sariannidis et al., 2013). In 1992, Munasinghe introduced three major poles to the definition of sustainability: economic, social, and environmental (Munasinghe & Cutler, 2007). In the use of different approaches to address the challenges of sustainability, Ponta (Ponta, Raberto, Teglio, & Cincotti, 2018) proposed the use of agent based macroeconomic models to analyze energy policies to foster the sustainability transition. In the same filed, Wolf (Wolf, Schütze, & Jaeger, 2016) analyzed the benefits of different computational models and their benefits as tools to help decision makers regarding the relation between climate change and growth.

However, due its complexity, only a limited number of studies had tested the three axes of sustainability and the interrelationship of its variables in the same framework (Bekhet, Matar, & Yasmin, 2017; Fodha & Zaghdoud, 2010). The idea of a causal relationship between energy consumption and economic growth was first introduced in the influential paper of Kraft (J. Kraft & Kraft, 1978b), once the causality relationship between them has important policy implications. The debate about what becomes first, economics or environment, no matter at local or global level was settled and the functional relationships between economic growth and environmental degradation were masterfully expressed by the Environmental Kuznets Curve (EKC), an inverted U-shape curve (David I. Stern, 2004). This dilemma about economic activity and pollution opened up paths for a rich research agenda (Moutinho et al., 2017). A literature review on the EKC starts with the seminal research from Grossman and Krueger (Gene M Grossman & Krueger, 1995) in their attempt to explore the path of sustainable development theory to describe the environmental degradation-economic growth relationship. Then, many scholars have been developng empirical studies of the EKC hypothesis in single or multiple countries, even regions, applying different econometric methodologies (Bo, 2011; Dinda, 2004; Ozturk, 2010; David I. Stern, 2004). Other researches have focused their attention on different environmental dimensions (i.e., CO_2, SO_2, particulate matter, wastewater, protected areas) or time contexts. Mixed and even inconclusive findings are still reported (Rahman & Kashem, 2017). Scholars found that the relationship presented multiple shaped EKC such as U, inverted-U, N, etc. Additionally, there were also evidences that the testing results depended on the specific econometric models (Chowdhury & Moran, 2012). Several authors have reviewed and summarized the vast literature of the EKC, the contributions of Kaika among others (Bo, 2011; Kaika & Zervas, 2013a, 2013b; David I. Stern, 2017) offers an overview of the relevant past empirical studies.

Despite all this wide gamma of research, the role of an exergy variable has not been tested to find the EKC, then exergy analysis is proposed with the goal to enrich sustainability and exergy as elements of environmental studies, once exergy links thermodynamic principles and systems under study with the environment (Marc A. Rosen & Dincer, 2001). Loiseau (Loiseau et al., 2012) compared environmental assessment tools and methods and quotes that among others, exergy analysis are part of the "energy family of methodologies" applying thermodynamics to sustainability able to study cities or industries (Geng, Zhang, Ulgiati, & Sarkis, 2010; Enrico Sciubba & Ulgiati, 2005b; Vega-Azamar, Romero-López, Glaus, Oropeza-García, & Hausler, 2015).

Exergy has been evolving over the years, as shown by Sciubba (E. Sciubba, Wall, G. , 2007) in his essential brief commented history on exergy. From the theoretical concepts of Carnot and Gibbs, the research by Reistad (G. Reistad, 1975b); as a notion to resource accounting approaches by Wall (Jan Szargut et al., 1987; Göran Wall, 1977a); the efficiency improvements in industrial equipment or power cycles and its components (Lozano & Valero, 1987), complex systems analysis (Enrico Sciubba et al., 2008), sectors and extended exergy analysis in societies or countries (Ayres, Ayres, & Warr, 2003; Ertesvåg, 2001; M. A. Rosen, 1992; G Wall, 1991). To the more recently link to the environment studied by Dincer and Rosen (Dincer & Rosen, 2013a) in their comprehensive *Exergy: energy, environment and sustainable development*. The conducted studies on exergy analysis of the industrial sector are classified into three main subsections: countries; industrial subsectors or industrial activities; and industrial devices (BoroumandJazi et al., 2013).

Romero in his review of the state of the art indicators for sustainability, claims the suitability of using exergy as an indicator for energy sustainability studies, also exergy can serve as a link to fill gaps in the generation of economic and environmental indicators (Romero & Linares, 2014). Gong established that “to improve energy and material conversion processes, the exergy concept should be applied. Therefore, exergy analysis is a tool to create and maintain a sustainable or rather a vital society” (Gong & Wall, 2016). Researchers also claim that exergy brings opportunities in decision-making to increase energy efficiency and energy conservation (Utlu & Hepbasli, 2007a). In parallel, exergy analysis was also studied regarding the environment and sustainability (Dincer & Rosen, 2004; M. A. Rosen, - Dincer, Ibrahim, 1997).

It may be reported that to the best of authors' knowledge, there is no work on the review of exergy analysis and the CO_2 emissions involving the EKC theory regarding the industrial sector. This research is expected to contribute to fill this gap. The aim of this work is to examine correlations between economic growth, energy consumption and CO_2 emissions. We use a data panel of ten countries from 1971 to 2014 to examine relationships between energy consumption and economic growth.

First, we examine these variables using a simplest specification of the EKC hypothesis, a linear equation with aim to test the influence of an exergy indicator as a control variable and its effects. Second, a panel fully modified ordinary least squares method is used to test the significance of the model. Similar to previous studies, we find that the two variables are both integrated of order one. The rest of the paper is organized as follows: Section 2 describes the data that is used in the empirical research. Section 3 displays the exergy analysis and the econometric methodologies. Section 4 presents empirical results and the interpretations. Section 5 concludes the paper with some policy implications.

3.2 Data sources

In this study, yearly data of GDP (in constant 2005 US dollars) and energy consumption (million tons oil equivalent) is revised for a set of ten countries (a mix of five developed and five developing countries, includes: Brazil, Canada, China, Italy, Mexico, Norway, South Africa, Turkey, the UK and the U.S.A.) to investigate the relationship between CO_2 emissions, energy consumption and economic growth. Data from the IEA database (International Energy Agency (IEA), 2017b) and the report “CO_2 Emissions from Fuel Combustion, IEA 2017” ((IEA). 2017), was achieved and analyzed chronologically from 1971 to 2014. The temporal dimension was restricted due to data availability.

3.2.1 Countries selection criteria

3.2.1.1 Socio-economic criteria

According to the World Bank to pay attention to the economical–social–environmental challenges of the future, the upper-middle-income countries, whose industrialization process increased strongly, need to be assessed deeply (World Bank, 2014). The idea to contrast two sets of countries is based on the socio-economic and environmental changes through the last four decades. The selected sample consists of a mixture of developed and developing countries. Between them, there are similarities: economic growth, geographical, population and the production of manufacturing goods to exports. Another interesting factor is that usually, some developing countries evolved from an economic base of agriculture towards manufacturing (Magazzino, 2014).

Agreeing their economic and social development, a key factor in terms of data availability was that most of them share an association with two international institutions: The Organization for Development and Economic Co-operation (OECD); and the International Energy Agency (IEA). Additionally, nine out of ten countries are part of the G20 countries.

3.2.1.2 Environmental criteria

Four of them were listed as the world's major GHG emitters (Nejat, Jomehzadeh, Taheri, Gohari, & Abd. Majid, 2015). The Climate Change Performance Index (CCPI) 2014 report ((IEA). 2017; Burck, Marten, Bals, & Höhne, 2014) assesses and compare the climate protection performance of 58 countries, that are, jointly, responsible for more than 90 percent of global energy-related CO_2 emissions , the results for the selected countries were the following: Canada and Turkey received a "very poor rank", the 58th and 54th; China, United States, South Africa, Brazil received a "poor" rank, the 46th, 43rd, 39th and 36th; Norway, Mexico and Italy received a "moderate" rank, the 24th, 20th and 18th; while the United Kingdom received a "good" rank, the 5th. Table 3-1 shows the trends of change on the environmental variable, carbon dioxide emissions, between the years 1971 to 2014. It reveals the difference among the ten countries in terms of CO_2 emissions, highlighting the previously cited ranks.

Table 3-1 Environmental variable, comparison of variation coefficients from the years 1971 to 2014

Country	**1971 ffCO₂ Emissions**	**2014 ffCO₂ Emissions**	**Rate of Growth**	**Mean**	**Standard error**	**CV**
Units	Mton/year	Mton/year				
Mexico	93.7	431	4.6	291	238.4	0.82
Canada	340.1	555	1.6	453	151.8	0.33
USA	4288.1	5,176	1.2	4988	628.0	0.13
Italy	289.3	3,120	1.1	376	21.5	0.06
Norway	23.0	35	1.5	30	8.7	0.29
United Kingdom	621.0	408	0.7	537	150.7	0.28
China	789.4	9,135	11.6	3,324	5,901.2	1.78
South Africa	157.1	437	2.8	277	198.2	0.71
Turkey	41.7	307	7.4	151	187.7	1.24
Brazil	87.5	476	5.4	234	274.8	1.17

3.3 Methods

This study analyzes the relationship between carbon dioxide emissions, energy consumption and economic growth, with the addition of an exergetic control variable to test the EKC hypothesis. First, we describe the exergy analysis methods, followed by a descriptive statistical analysis based on a statistical generalized linear model (GLM). Last, an econometric analysis including an ordinary least square analysis. The three steps are described below:

1. Exergy Analyzes to Compute Exergy Consumption and Exergy Intensity
2. A Descriptive Statistical Analysis to Detect Linear Correlations (R) between the variables
3. An Econometric Analysis, Including an Ordinary Least Squares Analysis (OLS)

A data set of 440 observations was study in this research. The carbon dioxide emissions per capita (CO_2/Capita) measured in metric tons per person was considered as the environmental decline variable. The growth variable is estimated by the per capita GDP, measured in United States dollars in 2005 prices. Since exergy can serve as a link to fill gaps in the generation of economic and environmental indicators, to serve as control variables, two exergetic variables were computed: exergetic consumption and exergetic intensity. In a global economy, the selected ten countries have been increasing their economic or commercial trade; accordingly, the specific impact of trade was analyzed through the trade openness variable. A list of abbreviations and meanings of the variables utilized in this study is presented before the references.

3.3.1 Exergy analysis theoretical background

An energy and exergy analysis of the selected ten countries was carried out, from the period 1971–2014; the energy intensities were taken from the IEA databases, to compute the exergy intensities. This is a key part of the innovative approach of this study in the search for the EKC hypothesis; which consists of proposing exergetic indicators as control variables.

Scholars have been studying exergy analysis on a large-scale base, such as a country, its society or their own economic sectors (Ertesvåg, 2001; Göran Wall et al., 1994). In 1997, Dincer (Dincer, 1997) assessed the energy consumption of the industrial sector in Canada to increase its efficiency based on exergetic analyses. To formulate an exergy balance of a non-constant flow system (like mass or energy balances), a common scenario requires establishing a control volume as well as a reference environment; it is usually established through a temperature T_0 = 25 °C and a P_0 =1 atm (M. A. Rosen, 1992). The flow of exergy entering in a system can be best described as the sum of the totality of their exergies (physical, chemical, potential, kinetic and nuclear exergies) (Marc A. Rosen, 2013):

$$Exergy_{sys} = Exergy^{Ph} + Exergy^{Kn} + Exergy^{Pt} + Exergy^{Ch} + \cdots \tag{3.1}$$

3.3.1.1 Exergy of a flowing stream of matter

In principle, the exergy of matter can be determined by letting it be brought to the dead state by means of reversible processes. The basic formulas used in exergy analysis modelling are given below. The total exergy can be divided into two-parts: physical exergy (thermo-mechanical exergy) and chemical exergy. The specific total exergy of the flowing stream of matter can be expressed as:

$$Exergy = Exergy^{Ph} + Exergy^{Ch} \tag{3.2}$$

The first part of Equation (1) represents the physical exergy, while the second represents the chemical exergy. The physical exergy is the maximum work obtainable by taking the matter through reversible processes from its initial state (temperature: T and pressure: P) to the state determined by the environmental conditions (temperature: To and pressure: Po). The chemical exergy is the maximum work that can be obtained by taking a substance having the parameters (T_o, P_o, mj_o) to the state determined by the dead state (T_o, P_o, mj_o).

3.3.1.2 Exergy of fuels

On industry, the most common mass flows are hydrocarbon fuels at near-ambient conditions; then the term $Exergy^{Ph}$ in Equation (2) is approximately zero, as a result the exergy reduces to chemical exergy ($Exergy^{Ch}$); next it can be written as (A. Al-Ghandoor et al., 2010; Guevara et al., 2016; M. A. Rosen, 1992; Utlu & Hepbasli, 2007b):

$$Exergy \quad = \gamma_f HHV_f \tag{3.3}$$

Where γ_f denotes the exergy grade function or exergy factor of the fuel, defined as the ratio of chemical exergy to the higher heating value ($HHVf$). With the use of the exergy factor, conversions of energy data to exergy values of energy carriers are given by a proportionality constant (Bühler et al., 2016; Guevara et al., 2016). In other words, due to the complexity of the chemical composition of fuels, a simple approach was applied, since the higher heating value ($HHVf$) is close to the chemical exergy. In this paper, the average exergy grade functions for different energy carriers are considered, extracted from several sources (Ertesvåg, 2001; M. A. Rosen, 1992; Utlu & Hepbasli, 2007a). There are also other fuels obtained as by products from the different processes in the manufacturing sector.

3.3.2 Linear correlations coefficients (*R*) detection

First, in a set of 44 observations, the annual averages are calculated by country for each variable, proceeding to estimate the correlations based on the variable $pcCO_2$. Secondly, the complete data were analyzed, by the year and by country (440 observations) in function of $pcCO_2$.

Subsequently, a descriptive statistical analysis is developed, based on empirical tests, with the aim of detecting the strength and direction of a linear relationship and proportionality between two study variables, by means of a linear correlation (R) among the proposed variables. Table 3-2 describes the total set of variables applied in this study in search of the existence of the EKC.

Table 3-2 Multivariable framework summary (International Energy Agency (IEA), 2018)

No.	Abbreviation	Description	Units
1	$pcCO_2$	CO_2 Emissions	Mt of CO_2/year/Capita
2	$ffCO_2$	CO_2 Emissions from fossil fuels	Mton/year
3	pcTPES	Total Primary Energy Supply	toe/Capita
4	pcGDP	GDP per capita; USD 2005	Billion USD, 2005
5	Tr opn	Trade openness	%
6	ffEn con	Energy consumption from fossil fuels	PJ/year
7	En int	Energy Intensity	TPES/GDP
8	C int	Carbon intensity	Mton/year
9	Ex con	Exergy Consumption	PJ/year
10	Ex int	Exergy Intensity	TPES/GDP

Prior to the econometric analysis, the data sets were being analyzed and the moderate correlation coefficients ($-0.5 < R$) and ($R > 0.5$) were identified (Zilio & Recalde, 2011).

3.3.3 Econometric analysis

To test the existence of the EKC hypothesis, a model using panel data estimation techniques was developed. The approach on this research adjusts to the simplest specification of EKC hypothesis, a linear equation, with the aim to test the viability of exergy indicators and its possible effects. Additionally, to test the significance of the model, an ordinary least squares analysis (OLS) was developed.

EKC literature refers to four main hypotheses to explain the direction of the relationship between energy consumption and economic growth: growth, conservation, feedback and neutrality (Ozturk, 2010; Shahbaz, Loganathan, Zeshan, & Zaman, 2015). The growth hypothesis validates a unidirectional causality flowing from energy consumption to economic growth. The conservation hypothesis argues that there is a one-way causality flowing from economic growth to energy consumption. The feedback hypothesis validates that energy consumption and economic growth cause each other. The neutrality hypothesis contents that there is no causality flowing between economic growth and energy consumption.

According to Grossman and Krueger, Panayotou, De Bruyn, Dinda, among others, the generalized functional form of the equation to test the EKC is presented as follows (De Bruyn, 1997; Dinda, 2004; Gene M Grossman & Krueger, 1995; Panayotou, 1997):
$D = f\ (EG_{it}, EnC_{it}, ExC_{it}, TrO_{it}, \mu_{it}\ ).$

where *ED* = Environmental degradation = ffCO_2; *EG* = Economic Growth = pcGDP; *EnC* = Energy consumption = En con; *ExC* = Exergy consumption = Ex con; *TrO* = Trade openness = Tr opn and $\mu_{i,t}$ = error terms. The Environmental Kuznets Curve for lineal models can be written as follows:

$$CO_{2t} = \beta_{0it} + \beta_{1it} * GDP + \mu_{it} \tag{3.4}$$

In this research, an extended form of the model, used to investigate the influence of an exergetic variable on the environment, can be described as follows:

$$\begin{aligned} ffCO_2 = {} & \beta_1 * GDP + \beta_2 * ffEn\ con + \beta_3 * Ex\ con + \beta_4 * Ex\ int \\ & + \beta_5 * pcTPES + \beta_6 * Tr\ opn \end{aligned} \tag{3.5}$$

3.4 Results and discussion

3.4.1 Energy and exergy analysis

This section discusses the measurement concept of exergy indicators, presents the new data set, and clarifies the relationship between energy losses and exergy indicators. Energy and exergy analysis were developed to calculate exergetic variables from a selected panel of ten countries, from 1971 to 2014. Starting with the compute of the energy and exergy inputs by selected countries, Table 3-3 shows the results of exergy input consumption (PJ) as an example for the year 2014; energy carriers were considered, with fossil fuels largely highlighting as the main source for most of the countries and along the 44 years spanned.

Table 3-3 Exergy consumption rates of countries, year 2014

Energy Carriers (Ktoe)						
Country	**Hydrocarbons**	**Renewables**	**Nuclear**	**Electricity**	**Heat**	**Total Exergy Consumptions (PJ)**
Mexico	173,077	16,989	2,446	45	0	8,060
Canada	208,128	51,229	27,119	3,923	0	12,597
USA	1,878,318	167,673	209,961	4,576	0	99,790
Italy	116,650	29,163	0	3,760	0	6,829
Norway	15,508	13,489	0	1,340	59	1,771
United Kingdom	151,000	14,433	16,115	1,765	0	7,974
Turkey	112,122	12,390	0	452	0	5,213
China	2,819,883	259,014	33,504	202	0	131,083
South Africa	132,893	18,187	3,487	229	0	6,471
Brazil	183,308	129,313	3,888	2905	44	13,375

Table 3-3 contains interesting information; first the use of fossil fuels still has a strong tendency to increase along the 44 years observed in the ten countries; highlights that hydrocarbons are the main energy carrier with rates from 47% to 90%, despite remarkable consumption rates of natural gas near 30%. Shahbaz found that coal consumption significantly deteriorates environmental quality. Particularly, Data shows that coal plays a key role in China and South Africa; both countries have important coal reserves, just South Africa owned 3.68% of the world coal reserves by 2009 (Shahbaz, Kumar Tiwari, & Nasir, 2013). The primary energy needs in both countries is based in Coal, near 70% by 2015 (International Energy Agency (IEA), 2017a).

Renewable fuels are employed at higher rates than 10% in six of ten countries, highlighting Norway with a highest 48%, followed by Brazil with 39%. According to the IEA, China, the U.S.A., Canada, the UK, Brazil, Turkey, Italy and Mexico are listed among the worldwide major producers of iron, steel and cement (International Energy Agency (IEA), 2008b). The most important topic in exergy analysis is the second law efficiency. Due to continuous increases in the energy price in the last forty years, engineers tend to utilize thermal systems or components that have maximum second law efficiencies, in industrial processes or devices. In this way, they can be confident that the best way to use the energy source thus, minimizing the expenditures.

In parallel, energy security is an essential ingredient to development. Therefore, increasing energy consumption may be one of the fundamental aspirations of developing regions such as Latin American, Asian and African countries (Pereira, Freitas, & da Silva, 2011; Zilio & Recalde, 2011). Paired with energy increase to satisfy societal demands, another key factor to boost energy security is minimizing energy lost or degradations in the form of inefficiency. Hereafter, it is important to create datasets of exergy indicators to improve energy efficiencies, consequently to enhance energy security.

Degradation of energy matters because it might be a consequence of process inefficiency or environmental impact producing materials, i.e., GHG (Gong & Wall, 2016; E. Sciubba, Wall, G. , 2007; Utlu & Hepbasli, 2007a). According to Hepbasli (Hepbasli, 2008), exergy is concerned with the quality of energy to cause change, degradation of energy during a process, entropy generation and the lost opportunities to do work. Then exergy is a fitted tool to improve efficiency in manufacturing. According to Rosen exergy is a measure of environmental degradation, consequently a tool to minimize environmental harm.

Then, exergy is a key component to sustainability. Moreover, exergy indicators are essential to distinguish the quality between energy resources (Dincer, 2002). Higher amounts of degradation of energy inside the economic and environmental development performance of countries might cause larger environmental impacts affecting societies at local, regional or global levels (Marc A. Rosen & Dincer, 2001).

3.4.2 Linear correlations, empirical evidence

Many factors may have an impact in CO_2 emissions; in this study were examined four major contributors: energy consumption, exergy consumption, exergy intensity and GDP. Prior to the econometric analysis, the prearrangement of the database was based on two criteria: by year, by country and vice versa. In addition, the averages of the values per year for each variable were computed. Last, an analysis of the data applying the linear regression method to obtain the determination coefficients was applied. Table 3-4 shows the results of the correlation factors (R) between the different variables. As a result, ffCO_2 ($R^2 \geq 0.95$)

emissions correlations get bigger coefficients compared to those of $pcCO_2$ emissions ($R^2 \geq 0.7$) in terms of the control variables. Even when the present study does not consider individual tests for countries, however, compared with previous studies, in terms of statistical increases our results are similar to those of Alam (Alam et al., 2016), regarding the CO_2 emissions and energy consumption by Brazil and China.

After the first test with a set of 44 observations per variable, yearly averages per country for each was computed, proceeding to estimate the correlations based on the $pcCO_2$ as environmental deterioration; as a result, only three of them presented values of $R^2 \geq 0.95$ (pcTPES, ffEx cons, Tr opn). It is remarkable that Ex int shows negative but high values of $R^2 \geq 0.90$, explaining a linear but inverse or decreasing curves.

Table 3-4 Correlation coefficients matrix

	pcGDP (USD 2005)	**$pcCO_2$ ($MtonCO_2$)**	**$ffCO_2$**	**ffEn Cons (PJ)**	**En int (TPES/GDP)**	**Ex int (TPES/GDP)**	**pcTPES (TPES/GDP)**	**Tr opn (%)**
pcGDP	1	-	-	-	-	-	-	-
$pcCO_2$	0.654	1	-	-	-	-	-	-
$ffCO_2$	0.938	0.633	1	-	-	-	-	-
ffEx con	0.956	0.624	0.998	1	1	-	-	-
Ex int	−0.988	−0.537	−0.919	−0.940	−0.940	1	-	-
pcTPES	0.958	0.725	0.845	0.871	0.871	−0.927	1	-
Tr opn	0.949	0.624	0.989	0.990	0.990	−0.934	0.861	1

In economy, energy intensity is viewed as an indicator of the energy efficiency of an economy. It is calculated as the ratio between the energy consumption (*En cons*) and the gross domestic product (GDP) of a country, meaning the units of energy needed to produce a unit of economic growth (Ang, 2006). The dataset of the panel shows that energy intensity countries with high values are the five developed ones; contrarily the five developing countries show lower values, except by China with the higher of all of them but with a drastically decreasing trend. A deeper analysis in the datasets reveals that both energy and exergy intensities increased for developed countries plus China; but regrettably decrease in developing countries, pointing out opportunities to increase future efficiency, and exergy efficiency is a fitted tool regarding the industrial sector (R. Arango-Miranda, R. Hausler, R. Romero-López, M. Glaus, & S. P. Ibarra-Zavaleta, 2018b; M. A. Rosen, 1992; Utlu & Hepbasli, 2007b).

In fact, Energy efficiency is one of the main variables that induce a reduction in fossil-based energy consumption. In a study conducted by the International Energy Agency (International Energy Agency (IEA), 2015) shows that without the improvements made on energy efficiency during the period from 1973 to 2005 at global scale, the use of energy would have been 58% higher than the level recorded in 2005, highlighting the relevance of energy efficiency to reduce the energy request. However, since 1990, the energy efficiency rate has stagnated due to the lower economic interest affected by the relatively low price of fuels inducing an increase in the demand for oil (Proskuryakova & Kovalev, 2015). Considering the energy efficiency as a control variable (reciprocal of energy intensity), the results showed that his trend could be negative but statistically significant (R = 0.95).

3.4.3 Econometric analysis of empirical results

Several authors developed a literature survey on the nexus CO_2-energy-growth and the EKC, those overviews reveal similitudes with our work in terms of the time frame and some of the selected countries, however, once our empirical test was based on average values by country and year, then it was not possible to study countries solely as it was not the goal of this work (Moutinho et al., 2017; Ozturk, 2010; Pasten & Figueroa, 2012; David I. Stern, 2017). It is important to understand the relation between renewable and non-renewable energy consumption, CO_2 emissions and economic growth in terms of revealing the dependence of the economy on energy and designing the energy policies (H. Khobai & Le Roux, 2018). Table 3-5 displays the results of the variables used in the analyses of the EKC; it is observed that there is a large dispersion between cross-section units (countries), mainly in the levels of per capita income.

The linear correlation result shows a positive trend between ffCO_2 vs. pcGDP, ffCO_2 vs. Ex con and ffCO_2 vs. Tr opn; as well as an inverted correlation of ffCO_2 vs. Ex int. This relation depicts the existence of the EKC for the panel, with a feedback hypothesis. Afterwards, regarding the test of the hypothesis cited by Apergis et al. (Apergis & Payne, 2009), in the present research work was detected that the pcGDP—exergy consumption relation confirms the growth hypothesis, similar to those results from Lee (Lee, 2005) by developing countries.

These findings are in line with Magazzino et al. (Magazzino, 2011) once energy consumption tends to be more responsive to economic growth in less developed than in advanced countries; however it is important to state that, according to them, the relationship between energy and economic growth activity could be affected by a variety of other factors.

Table 3-5 Summary of empiric results of the multi-variable framework

	Variables						
	pcGDP USD 2005	**$pcCO_2$ $MtonCO_2$/Cap**	**ffEn cons PJ**	**ffEx con PJ**	**Ex int TPES/GDP**	**pcTPES toe/Cap**	**Tr opn %**
Media	23,309	7.5	17,814	21,199	117.8	3.4	64.7
Median	14,844	6.6	6,748	8,030	117.7	2.6	48.6
Stdr Dev	21,027	5.7	28,038	33,366	28.0	2.5	70.5
Max	91,597	22.1	128,357	152,745	230.5	8.5	442.6
Min	263	0.9	558	664	44.3	0.5	9.1

In addition to this, an ordinary least squares analysis (OLS) was developed to test the significance of the model; the results are presented in Table 3-6.

Table 3-6 Regression results of $ffCO_2$ emissions and pcGDP

Variable	**Coefficient**
Correlation coefficient R^2	0.983
Determination coefficient R^2	0.965
Adjusted R^2	0.956
Standard error	0.064
Observations	44.000
Countries	10.000

The independent variables pcGDP, Ex con, Ex int, pcTPES and Tr opn explain 96.55% of the variation of ffCO_2. Besides, an analysis to test the global significance of the proposed model was developed, confirming its own validity. The overall effects of the model are significant since the null hypothesis is rejected due a low *p*-value ≤ 0.001. Table 3-7 shows the long run tests results.

Table 3-7 Regression of ffCO_2 emissions and pcGDP

	Coefficient	**Stdr. Error**	***t*-Statistic**	**Probability**	**Inferior 95%**	**Superior 95%**
Interception	−7.843	0.787	−9.968	0.000	−9.440	−6.250
pcGDP	0.000	0.000	3.168	0.003	0.000	0.000
Ex con	0.000	0.000	−1.688	0.100	0.000	0.000
Ex int	0.037	0.010	3.813	0.001	0.020	0.060
pcTPES	0.961	0.257	3.735	0.001	0.440	1.480
Tr opn	0.005	0.005	1.008	0.320	−0.010	0.020

Thus, it was observed that the forecaster variables pcGDP, Ex int and pcTPES are statistically significant because their p-values are low (<0.05). However, the p-value for Tr opn (0.320) and Ex int (0.001) is greater than the common alpha level of 0.050, and an indication of statistically insignificant variables. Trade openness was also found statistically insignificant to Canada by Olale (Olale et al., 2018). In comparison with past studies, the statistical insignificance of trade openness is different from those who find the variable negatively related to per capita CO_2 emissions, especially in higher-income countries (Ben Jebli et al., 2016). Accordingly, Shahbaz found trade openness improves environmental quality, and Jebli claims that if it is combined with renewable energies, are efficient strategies to combat global warming.

The growth of ffCO_2 emissions and pcGDP in the first part of the curve is validated, since the increase in economic growth goes simultaneously with the degradation of the environment. Once it is observed that the sign of the quadratic term is positive, this implies that in a second stage, when the pcGDP remains increasing, it also grows the carbon dioxide emissions, non-validating the second part of the environmental curve. This result could be expected due the comparison of the mixed sample of developed and developing economies.

Our finding is in accordance with what Kaika established, since the developed countries have shown evidence of the EKC, contrary to the developing countries (Kaika & Zervas, 2013a, 2013b). As an example, causality running from energy consumption to GDP, or the evidence in the existence of the EKC are more valid in the developed countries compared with the developing ones (Chontanawat, Hunt, & Pierse, 2008).

Usually in developed countries, growth or feedback hypothesis is reported, and the curve changes its slope to negative for the reduction of emissions, considering that the country reached a level of economic stability where the degradation of the environment tends to decrease, making intensive use of green technologies (Lee, Chang, & Chen, 2008). On the contrary, developing economies, particularly China, the CO_2 curve trend tend to remain increasing along the chosen timeline, as a consequence a growth hypothesis is suggested (Yiping Fang, 2011; X.-P. Zhang & Cheng, 2009).

These results are in accordance with previous authors, due the influence of several external factors producing ups and downs trends in the curves (Özokcu & Özdemir, 2017; Ozturk, 2010). Also interesting is the correlation between $pcCO_2$ and exergy consumption, it shows a negative trend, describing possibly an inverted *N* shape. This result opens the door to future research with the use of exergetic indicators, with the possibility to link exergy efficiency and the use of renewables in countries (Gong & Wall, 2016). Hence, detection of degradation of energy through exergy indicators is becoming a prominent topic in energy and environmental literature (Dincer, 2002; Dincer & Rosen, 2004; Romero & Linares, 2014; M. A. Rosen, - Dincer, Ibrahim, 1997). Energy analysis has been widely used by academics and government agencies. Among others, Hammond (Arango-Miranda et al., 2018b; Hammond & Stapleton, 2001) has argued that it is important for practitioners and policy makers to employ exergy analysis as a complement to the existing methods to develop datasets, official reports and environmental and energetic strategies. It is necessary to increase the contribution of exergy to the environment.

Although this is a small sample of the panel model of countries, the results of our study extend the debate of previous research in the use of the timeline, a set of chosen countries, control variables or other external factors i.e., technology, socio-political issues. According to a critical literature review , controversy still surrounding the EKC hypothesis, based on the overall empirical evidence.

The main issue comes up to be how the income-pollution relationship evolves when the EKC-concept ceases to be valid. Previous studies show that developing countries are expected to behave differently than developed countries since socio-economic-political unique conditions change over time. (Kaika & Zervas, 2013b). Policy makers are therefore to exercise caution in their efforts to promote economic growth and at the same time reduce environmental degradation keeping in mind the sustainability of both the economy and the environment (Alam et al., 2016).

3.5 Conclusions

Series data from the period 1971–2014 for ten countries were analyzed in a comparative empirical study of selected developed and developing countries. The whole period of 44 years, neutrality hypothesis was confirmed by OECD countries such as Canada, Mexico, Norway, Turkey, the UK and the USA. It means that there is no causality amid economic growth and energy consumption. Comparing the long run correlations between CO_2 emissions from fossil fuels, GDP per capita and exergy consumption, a positive correlation trend was observed, denotes that by improving energy efficiency policies and regulatory instruments, the efficiency of the system under study tends to improve, accordingly decrease emissions and environmental impacts. The EKC was not confirmed, therefore, the efforts to reduce GHGs emissions like Kyoto Protocol proves insufficient, as permanent patterns for reducing CO_2 emission is not observed for the afore mentioned countries.

The results confirm the existence of strong correlations between the multi-variable frameworks, excepted by the carbon intensity. Additionally, a long-term feedback hypothesis among CO_2 emissions from fossil fuels, GDP per capita and exergy consumption was confirmed. Furthermore, and inverted-strong correlation between CO_2 emissions from fossil fuels and exergy intensity are detected, offering an insight for future efficiency improvements. Finally, results from developed countries have been increasing their effectiveness to manage environmental problems, especially, CO_2 emissions.

Similar to previous research, the use of renewables or natural gas seems to be the right way to combat global warming and reduce CO_2 emissions, enabling the reduction of energy dependency and promoting energy security. It is remarkable that restrictions on the use of energy can negatively affect economic growth, while increases in energy can contribute to economic growth. Consequently, it is concluded that energy is a limiting factor for economic growth and, therefore, the impacts on energy supply will have a negative impact on economic growth.

Regardless results do not support the EKC hypothesis, however, exergy intensity opens the door for future research once it proves to be a useful control variable. Exergy provides opportunities to analyze and implement energy and environmental policies in these countries, once is a tool to minimize environmental harm, with the possibility to link exergy efficiency and the use of renewables.

Future research should be focus on expanding the model and digging into its complexity, thus the inclusion of exergetic variables. Another venue could be focused to develop a deeper analysis at regional or country scale, regarding the correlations of environmental and exergetic indicators. As a final point, one of the main limitations to our study is the availability of data, mainly in years before 1970 and specifically for developing countries. This problem should be overcome through the help of international organizations and institutions.

CHAPTER 4

ECONOMIC GROWTH, ENERGY AND THE ENVIRONMENTAL KUZNETS CURVE IN NORTH AMERICAN COUNTRIES (NAFTA PARTNERS)

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Abstract:

The increase in the population, GDP and exports in the last decades has resulted in the growth of the industrial sector and the transportation of goods; industry represents about 50% of the total energy consumption and more than 30% of the total Carbon dioxide (CO_2) emissions particularly in the North American region. This study is an attempt to investigate the nexus among carbon dioxide (CO_2) emissions, gross domestic product (GDP), and energy-exergy consumption within the framework of the environmental Kuznets curve (EKC), in a 1990–2014 sample of North American Free Trade Agreement (NAFTA) countries (Canada, Mexico and the USA). Additionally, exergy indicators and the human development index (HDI) are examined in this work. For this purpose, ordinary least squares, co-integration, and causality tests for the data sets are conducted. Results provide evidence in favor of the EKC hypothesis for Mexico and the USA Furthermore, in the case of Mexico, it was found that increasing renewable exergy share lowers CO_2 emissions; on the contrary, increasing HDI will grow CO_2 emissions. The Granger causality analysis underscores feedback hypothetical links among CO_2 emissions, economic growth, energy consumption, trade openness, exergy intensity and renewable exergy consumption in the long run. Some policy implications are highlighted for NAFTA countries' policymakers not only for tackling CO_2 emissions, but also for promoting growth in the renewable energy share. The addition of the exergetic indicator provides an interesting insight on energy and environmental strategies.

Keywords: climate change; energy; exergy analysis; industrial sector; NAFTA; exergetic renewable share; sustainability.

4.1 Introduction

As widely accepted, the increase of anthropic greenhouse gas and aerosol emissions into the atmosphere from the use of traditional fossil fuels adds pressure on the environment contributing to destabilizing the main natural cycles involved (the resulting global warming is a major and inevitable corollary of current world energy policy) (Focacci, 2005). Carbon dioxide (CO_2) has a leading role within this context and, as a consequence, both more stringent measures about fossil-fuel burning (the main source in anthropic production of polluting effluents from combustion) and those actions regarding more rational employment of the same source have become the leitmotif of international debates on the topic. In the market economies, carbon taxes or emission permits are some of the most important legal instruments used to act in such a direction (Evans, 2003; Leimbach, 2003).

For developing countries, the challenge to sustain economic growth while dealing with energy needs is exacerbated by demographic increase. As a matter of fact, population increase and subsequent social and economic transformations have a particular concern also for the relationship with not homogeneous distribution of people. The United Nations Secretariat projections (U. Nations, 2015) estimate the world population is projected to reach 9.8 billion by 2050. As far as the developing countries are concerned, the percentage of inhabitants living in urban areas should increase to 60% in 2025 (compared to 45% in 1994) and raising even more up to 80–90% (average level for developed countries).

Globally, quantification of energy-related CO_2 emissions are of serious concern for the policy makers to make efficient environmental policies without damaging the economic growth (Dong, Wang, Deng, Wang, & Zhang, 2016). Energy is an essential input in the economic activity process. The rates of worldwide economic development indicate that increased energy demand at all sectoral levels may represent a threat to the achievement of global reduction objectives for 2050 (Intergovernmental Panel on Climate Change (IPCC) UNEP, 2016). According to the IPCC, the combustion of fossil fuels unavoidably produces

GHGs, comprising mainly CO_2, among others. A fast wave of global economic growth between 2005 and 2013, influenced global GHG emissions, increasing 18.3% and reaching more than 35 billion tons by 2013 (Environment and Climate Change Canada, 2018). Virtually 90% of the CO_2 emissions has a fossil-fuel source and therefore are determined by the energy demand or the level of energy-intensive activity. After periods of economic growth without considering environmental damage, academics, practitioners and policy makers, aware of the risk related to industrialization and deforestation processes, react starting a discussion (Vlontzos et al., 2017). This dilemma between the importance of economic growth without compromising our natural resources opened up grounds for a rich research agenda (Moutinho et al., 2017).

4.2 The EKC, sustainability, energy and exergy analysis

How to confront the problem of climate change is a great challenge. Sustainability offers an approach to combat GHG and CC. In late 80s, efforts from governmental and non-governmental organizations mainly in industrialized countries, were the first steps in the route of sustainable development (Robinson, 2004). To control the carbon emissions issues, governments have been taken actions to face this challenge (Turki et al., 2018).In order to study the trend and affecting factors of CO_2 emissions in different production sectors and to promote the green economic development, several studies have been conducted on relationship among economic growth, energy consumption and CO_2 emissions. Furthermore, even different strands based on the search for the environmental Kuznets curve (EKC) theory, or the causal correlations among variables or combining different socio-economic and environmental variables (Sharif Hossain, 2011).

In the first years 1992, Munasinghe introduced three major poles to the definition of sustainability: economic, social, and environmental (Munasinghe, 2009). Applying different approaches to address the challenges of sustainability, Ponta (Ponta et al., 2018) proposed the use of agent based macroeconomic models to analyze energy policies to foster the sustainability transition. In the same field, Wolf (Wolf et al., 2016) studied the benefits of different computational models and their benefits as tools to help decision makers regarding the relation between climate change and growth.

However, due to its complexity, only a limited number of studies had tested the three axes of sustainability and the interrelationship of its variables in the same framework (Bekhet et al., 2017; Fodha & Zaghdoud, 2010). The idea of a causal relationship between energy consumption and economic growth was first introduced in the influential paper of Kraft (J. Kraft & Kraft, 1978a), once the causality relationship between them has important policy implications. The debate about what becomes first, economics or environment, no matter at local or global level was settled and the functional relationships between economic growth and environmental degradation were masterfully expressed by the Environmental Kuznets Curve (EKC), an inverted U-shape curve (David I. Stern, 2004). This quandary about economic activity and pollution opened up paths for a rich research agenda (Moutinho et al., 2017).

A literature review on the EKC starts with the seminal research from Grossman and Krueger [21] in their attempt to explore the path of sustainable development theory to describe the environmental degradation-economic growth relationship. Then, many scholars have been developing empirical studies of the EKC hypothesis in single or multiple countries, even regions, applying different econometric methodologies (Bo, 2011; Dinda, 2004; David I Stern, 2007). Other researches have focused their attention on different environmental dimensions (i.e., CO_2, SO_2, particulate matter, wastewater, protected areas) or time contexts. Mixed and even inconclusive findings are still reported (Rahman & Kashem, 2017). Scholars found that the relationship presented multiple shaped EKC such as U, inverted-U, N, etc. Additionally, there were also evidences that the testing results depended on the specific econometric models (Roy Chowdhury & Moran, 2012). Some scholars have reviewed and summarized the vast literature of the EKC, among others (David I. Stern, 2017), Kaika's work (Kaika & Zervas, 2013b) offers an interesting summary of the relevant past empirical studies.

It is important to understand the relationship between renewable and non-renewable energy consumption, CO_2 emissions and economic growth in terms of revealing the dependence of the economy on energy and designing the energy policies (H. Khobai & Le Roux, 2018). In this frame, the literature refers that there are four main hypotheses to explain the direction of the relationship between energy consumption and economic growth: growth, conservation, feedback and neutrality(Ozturk, 2010; Shahbaz et al., 2015). The growth hypothesis argues that energy consumption is a major factor in boosting economic growth and validates a unidirectional causality flowing from energy consumption to economic growth. The conservation hypothesis argues that there is a one-way causality flowing from economic growth to energy consumption. The feedback hypothesis validates that energy consumption and economic growth cause each other, that is, if exist a bidirectional causality running between energy consumption and economic growth. The neutrality hypothesis contents that there is no causality flowing between economic growth and energy consumption.

Despite all this wide gamma of research, the role of an exergy variable has not been tested to find the EKC, then exergy analysis is proposed with the goal to enrich sustainability and exergy as elements of environmental studies, once exergy links thermodynamic principles and systems under study with the environment (Marc A. Rosen & Dincer, 2001). Loiseau (Loiseau et al., 2012) compared environmental assessment tools and methods and quotes that among others, exergy analysis method is part of the "energy family of methodologies" applying thermodynamics to sustainability able to study cities or industries (Geng et al., 2010; Enrico Sciubba & Ulgiati, 2005a).

Exergy has been evolving over the years, as shown by Sciubba (E. Sciubba, Wall, G. , 2007) in his essential brief commented history on exergy. From the theoretical concepts from Carnot and Gibbs, the research by Reistad (G. M. Reistad, 1975), as a notion to resource accounting approaches by Wall (Göran Wall, 1977b), the efficiency improvements in industrial equipment or power cycles and its components (Lozano & Valero, 1987), complex systems analysis (Enrico Sciubba et al., 2008), sectors and extended exergy analysis in societies or countries (Ayres et al., 2003; Ertesvåg, 2001; M. A. Rosen, 1992). To the more recently link to the environment studied by Dincer and Rosen (Dincer & Rosen, 2013a) in their comprehensive Exergy: energy, environment and sustainable development.

The conducted studies on exergy analysis of the industrial sector are classified into three main subsections: countries; industrial subsectors or industrial activities; and industrial devices (BoroumandJazi et al., 2013). In his review of the state of the art indicators for sustainability, Romero claims the suitability of using exergy as an indicator for energy sustainability studies, also exergy can serve as a link to fill gaps in the generation of economic and environmental indicators (Romero & Linares, 2014). Gong established that "to improve energy and material conversion processes, the exergy concept should be applied. Therefore, exergy analysis is a tool to create and maintain a sustainable or rather a vital society" (Gong & Wall, 2016). Researchers also claim that exergy brings opportunities in decision-making to increase energy efficiency and energy conservation (Utlu & Hepbasli, 2007a), also carving in their influence in energy policy (Utlu & Hepbasli, 2009).

It may be reported that to the best of authors' knowledge, there is no work on the review of exergy analysis and the CO_2 emissions involving the EKC theory regarding the industrial sector. This research is expected to contribute to fill this gap. The aim of this work is to examine correlations between economic growth, energy consumption and CO_2 emissions. Data sets of NAFTA countries from 1990 to 2014 were analyzed. First, we examine these variables using the simplest specification of the EKC hypothesis; simultaneously, the influence of exergy indicators as a control variable and its effects were tested. Second, a set of statistical econometric test was developed to detect causal relationships among the set of variables.

The rest of the paper is organized as follows: Section 3 describes the analyzed countries. Section 4 displays data sets and the methodological steps applied, including the exergy analysis and the statistical econometric methodologies. Section 5 presents empirical results and the interpretations. Section 6 concludes the paper with some policy implications.

4.3 The NAFTA countries

Formed by three countries, in 2018 the population in the North American Free Trade Agreement (NAFTA) region reaches around 490 million people; the trade economy reaches a total GDP of 24.8 trillion and a per capita GDP of $50 700 US dollars. Geographically, this region owns an area of 21 578 200 km^2, being the world's largest free-trade area. The three countries together are the equivalent of 13.55% of the world's landmass (Liu, Hong, Li, & Wang, 2018). In comparison, the Eurozone, conformed by 28 countries, is the second-largest trade zone, with a population over 342 million, a GDP of 14 trillion and a per capita GDP of $41 000 US dollars; covering an area close to 2 753 900 km^2.

4.4 Data and Methodology

4.4.1 Data

In this study, yearly data of GDP (in constant 2005 US dollars) and energy consumption (million tons oil equivalent) is revised for a set of three countries: Canada, Mexico and the USA, to investigate the relationship between CO_2 emissions, energy consumption and economic growth. All of them will be considered as a block in the North American region. Data from the IEA database (International Energy Agency (IEA), 2017b) and the report "CO_2 Emissions from Fuel Combustion, IEA 2017" ((IEA). 2017) , was achieved and analyzed chronologically from 1990 to 2014. The temporal dimension was limited due to data accessibility.

4.4.2 Countries socio-economic and environmental profiles

In respect to the socio-economic profile, the World Bank urges the need to study developing countries, as Mexico, due its trade relations with developed economies and their inherent future social, economic, and environmental challenges of the future (World Bank, 2014). Among the three NAFTA countries are similarities: economic growth, geographical, population and the production of manufacturing goods to exports. The three countries belong to the Organization for Development and Economic Co-operation (OECD); and the International Energy Agency (IEA). About their environmental profile, the three selected North American countries were listed as the world's major top 20 GHG emitters (Nejat et al., 2015)]. The Climate Change Performance Index (CCPI) 2014 report (Burck et al., 2014) assesses and compare the climate protection performance of 58 countries, that are, jointly, responsible for more than 90 percent of global energy-related CO_2 emissions.

4.4.3 Methods

Following the empirical literature on the EKC hypothesis, data sets of three North American countries, from 1990 to 2014, were determined with the goal to examine causal correlations between economic growth, energy consumption and CO_2 emissions. To address the issue of omitted variables bias, the study incorporated trade openness, carbon dioxide emissions and capital formation as the additional variables to form a multi-variable framework. All the variables were converted into logarithms form to avoid heteroscedasticity. Table 4-1 shows a descriptive statistic summary of the variables, average values among between the years 1971 to 2014.

The proposed methodology consists of two main steps. Initially, an energy and exergy analysis was developed in the selected panel of countries, from years 1990 to 2014. The aim was to test them as exergetic variables. The carbon dioxide emissions (CO_2) are considered as environmental deterioration variable. The second step starts with a descriptive statistics of the variables analyzed in this research, described in Table 4-1 (logarithmic values). Initially, the statistical analysis consists in search of the EKC hypothesis. Followed by an analysis to detect causal correlations among the environmental, economic, social and the exergetic variables. The econometric part of the analysis consists of three tests: ordinary least squares (OLS), vector analytic regression (VAR) and the Granger test.

Table 4-1 Variable definitions and descriptive statistics (average values by 3 countries)

Variable	Units	Average	Max	Min	Median	Stdr Dev	Rate of Growth
lnCO_2 ff	Mton	7.6	8.6	5.5	6.2	5.0	1.41
lnEncff	PJ	10.5	11.5	8.6	9.3	7.8	1.37
lnGDPpc	USD, 2005	10.4	10.8	8.9	10.7	7.8	1.41
lnExint	TPES/GDP	4.6	4.8	4.3	4.6	1.3	1.40
lnExRS	%	2.4	2.9	1.5	2.3	0.5	1.41
lnTRopn	%	3.9	4.4	3.0	3.9	1.3	1.94
lnHDI	%	0.2	0.1	0.4	0.1	4.7	1.11

4.4.4 Exergy analysis

4.4.4.1 Theoretical Background (the exergy approach)

An energy and exergy analysis of the NAFTA countries was performed, from 1990 to 2014; the energy intensities were taken from the IEA databases, to compute the exergy intensities. This is a key part of the innovative approach of this study in the search for the EKC hypothesis; which consists of proposing exergetic indicators as control variables.

Scholars have been studying exergy analysis on a large-scale base, such as a country, its society or their own economic sectors (Wall, Sciubba et al. 1994, Ertesvåg 2001). In 1997, Dincer (Rosen 1992, Rosen and Dincer 1997) evaluated the energy consumption of the industrial sector in Canada to increase its efficiency based on exergetic analyses. To formulate an exergy balance of a non-constant flow system (like mass or energy balances), a common scenario requires establishing a control volume as well as a reference environment; it is usually established through a temperature T_0 = 25 °C and a P_0 =1 atm. (Rosen 1992). The flow of exergy entering in a system can be best described as the sum of the totality of their exergies (physical, chemical, potential, kinetic and nuclear exergies) (Rosen 2013).

$$Exergy_{sys} = Exergy^{Ph} + Exergy^{Kn} + Exergy^{Pt} + Exergy^{Ch} + \cdots \quad (4.1)$$

4.4.4.2 Exergy of a flowing stream of matter

The exergy of a flowing stream of matter can be determined by letting it be brought to the dead state by means of reversible processes. The basic formulas used in exergy analysis modelling are given below. The total exergy can be divided into two-parts: physical exergy (thermo-mechanical exergy) and chemical exergy. The specific total exergy of the flowing stream of matter can be expressed as:

$$Exergy = Exergy^{Ph} + Exergy^{Ch} \quad (4.2)$$

The first part of the equation (1) represents the physical exergy, while the second represents the chemical exergy. The physical exergy is the maximum work obtainable by taking the matter through reversible processes from its initial state (temperature: T and pressure: P) to the state determined by the environmental conditions (temperature: T_o and pressure: P_o). The chemical exergy is the maximum work that can be obtained by taking a substance having the parameters (T_o, P_o, mj_o) to the state determined by the dead state (T_o, P_o, mj_o).

4.4.4.3 Exergy of Fuels

On industrial facilities, the most common mass flows are hydrocarbon fuels at near-ambient conditions; then the term ExergyPh in Equation (2) is approximately zero, as a result the exergy of the fuel reduces only to the chemical exergy (ExergyCh) component; consequently, equation (3.2) can be written as (Rosen 1992, Al-Ghandoor, Phelan et al. 2010):

$$Exergy_f = \gamma_f HHV_f \quad (4.3)$$

Where γ_f denotes the exergy grade function or exergy factor of the fuel, defined as the ratio of chemical exergy to the higher heating value (HHVf). With the use of the exergy factor, conversions of energy data to exergy values of energy carriers are given by a proportionality constant (Bühler et al., 2016). In other words, due the complexity of the chemical composition of fuels, a simple approach was applied, since the higher heating value (HHVf) is close to the chemical exergy component. In this paper, the average exergy grade functions for different energy carriers are considered, extracted of several sources (Ertesvåg, 2001; M. A. Rosen, 1992). There are also other fuels obtained as by products from the different processes in the manufacturing sector.

4.5 Econometric analysis

To address the issue of omitted variables bias, the study incorporated trade openness, carbon dioxide emissions and capital formation as the additional variables to form a multi-variable framework. All the variables were converted into logarithms form to avoid heteroskedasticity.

The econometric analysis consists of three tests: ordinary least squares (OLS), vector analytic regression (VAR) and the granger test. With the aim to test the existence of the EKC hypothesis, a model using panel data estimation techniques was developed. The approach on this research adjusts to the simplest specification of EKC hypothesis, a linear equation, with the aim to test the viability of exergy indicators and its possible effects.

EKC literature refers that there are four main hypotheses to explain the direction of the relationship between energy consumption and economic growth: growth, conservation, feedback and neutrality (Ozturk, 2010; Shahbaz et al., 2015). According to Grossman and Krueger, Panayotou, De Bruyn, Dinda, among others, the generalized functional form of the equation to test the EKC is presented as follows (De Bruyn, 1997; Dinda, 2004; Gene M Grossman & Krueger, 1995; Panayotou, 1997):

$$ED = f\ (Enc_{it}, GDPpc_{it}, ExRS_{it}, Exint_{it}, Tropn_{it},\ HDI_{IT},\ \mu_{it}\ ) \qquad (4.4)$$

Where: *ED*=Environmental degradation = CO_2ff; *EnC*=Energy consumption of fossil fuels; *GDPpc* =Economic Growth per capita; *ExRS*=Exergetic renewable share: *Exint*=Exergy intensity; *TrOpn*=Trade openness; *HDI*=Human development index; *Tropn*= Trade openness; μ = error terms. Our analysis began considering a parametric model that is quite standard in the EKC literature and takes the following lineal model form:

$$\boldsymbol{E_t} = \beta_0 + \beta_1 * \boldsymbol{GDP_{it}} + \beta_2 * GDP^2_{2it} + \beta_3 * GDP^3_{2it}\, \mu + \boldsymbol{\Sigma^k_{j=1}}_{it} \boldsymbol{\gamma_j} \quad \boldsymbol{X_{J,IT}} + \mu_{it} \tag{4.5}$$

Where: E_t is per-capita CO_2 emissions; *Yt* is per-capita GDP and *Xt* is a vector of variables that may affect *Et*. The deterministic time trend (and sometimes its square) is included as a crude proxy of technological progress. In this research, an extended form of the model (Rehermann & Pablo-Romero, 2018), is applied to examine the influence of an exergetic variable on the environment, can be described as follows :

$$\boldsymbol{CO_2ff} = \boldsymbol{\beta_1 * GDPpc} + \boldsymbol{\beta_2 * GDPpc^2_{it}} + \boldsymbol{\beta_3 * GDPpc^3_{it}} + \boldsymbol{\delta_1 * Encff_{it}} + \boldsymbol{\delta_2 * ExRS_{it}} + \tag{4.6}$$

$$\boldsymbol{\delta_3 * Exint_{it} + \delta_4 * TRopn_{it} + \delta_5 * HDI_{it} + \mu_{it}}$$

4.5.1 Ordinary least squares test

The estimation of the equation (3.5) can be done by least squares ordinary (POLS). However, when considering a model with data panel that combines information over time and cross-section (countries), there is heterogeneity in cross-section observations that cannot be measured or unobservable by individual effects. However, POLS estimators can be inconsistent and biased. The way to include the unobservable effects is defining an error component model, where the error comprises the sum of two components: a random term and a second component that represents unobserved heterogeneity (Catalán, 2014).

The concept of heterogeneity can be understood as its own characteristics in cross-section units (countries) that cannot be measured and in consequence cannot be estimated. The conventional specification of panel data models with heterogeneity is represented as:

While working with time series, it is need to know if the data used presents the property of being stationary, otherwise the data must be handled with different statistical techniques to avoid that the regressions are spurious. For practical purposes to the scope of this study**,** it is determined that the data are not stationary, are of the same order of integration and that there is Granger causality in at least one sense.

4.5.2 VAR test

The empirical strategy proposed approach applies a panel-data Vector Auto Regression methodology. This technique combines the traditional VAR approach, which treats all the variables in the system as endogenous, with the panel data approach, which allows for unobserved individual heterogeneity. Here, we follow a similar strategy of (Magazzino, 2014). The impulse-response functions describe the reaction of one variable to the innovations in another variable in the system, while holding all other shocks equal to zero. The identifying assumption is that the variables that come earlier in the ordering affect the following variables contemporaneously, as well as with a lag, while the variables that come later affect the previous variables only with a lag. In other words, the variables that appear earlier in the systems are more exogenous and the ones that appear later are more endogenous.

4.5.3 Granger causality test

Following a traditional econometric procedure (Toda & Yamamoto, 1995), the Granger Causality among the variables under an augmented Vector Auto-regression (VAR) framework will be estimated. The appropriate maximum lag length is determined for the variables in the VAR by using standard methods (Rahman & Kashem, 2017). Specifically, the bases of the choice of lag length is on the usual information criteria, such as AIC. It is also need to ensure that VAR is well specified; that is VAR does not contain a serial correlation in the residuals.

4.6 Empirical Results

4.6.1 Ordinary least squares test

The analyzed variables were CO_2 emissions derived from total consumption of fuels, exergetic intensity, exergetic renewable share, energy consumption from fossil fuels, GDP per capita, trade openness and the HDI index. An overview of the analyzed countries shows curves of growth for most of the variables in the long-run. The curve with interesting performance is that of CO_2 emissions characterized mainly by a growing trend, with a behaviour mostly steady in the long run, but rather erratic for the USA. The data sets also highlight small punctual decreases, shared by the USA, Mexico and Canada. In this case of countries knotted in an economic and trade zone (NAFTA), an influence factor could be associated with common environment policies applied by the years 1983 and 1991 and 2009. In the long run, an important consideration arises, the presence of oil shocks impacts on progress towards less polluting technology and production (He & Richard, 2010).

Previously, scholars have applied the four hypotheses (Dinda, 2004; Özokcu & Özdemir, 2017) to explain the relationship between energy consumption and economic growth. There is also an augmented method, which is based on the behavior of the beta (β) factors and their influence on the EKC. Below, Table 4-2 shows the results to test the EKC hypothesis between the NAFTA countries.

Table 4-2 EKC parameters for NAFTA Countries

	Intercept	Encff	GDPpc	FREx	Exint	TRop	HDI
Coefficient		CO_2	β1	β2	β3	β4	β5
Canada	- 205.00	0.0083	(+) 0.0066	(+) 0.8955	0.3149	0.9521	281.00
Mexico	- 853.70	- 0.0042	(+) 0.0312	(-) 6.2000	2.0770	0.3340	1,136.00
USA	5 644.00	0.0814	(-) 0.0252	(-) 25.2700	- 4.7710	3.1670	- 6, 820.00

According to Özokcu, the evidence of an EKC requires a $\beta 1$ positive coefficient, a negative $\beta 2$ coefficients and a $\beta 3$ positive coefficient to obtain a quadratic relation to form a n inverted U shape; in our test, only the Mexican results show this form.The trend of the GDP per capita depicts a semi constant growth curve, predictable for developed and developing countries. It also emphasizes that the whole panel shows decreases for the year 2009, probably due to the crisis that began in the USA (G. P. Peters et al., 2012) whose global repercussions disturbed countries with industrial or intense trade activities.

In summary, a growing trend describes the behavior of some variables tested, particularly those of CO_2 emissions, energy consumption, economic growth, trade openness and human development index. In contrast, the decreasing trends of exergy intensity and exergetic renewable share are valid for the three countries. The main interest was focused to observe the CO_2 emissions behavior, with a general increasing pattern. However, with some small decreasing steps, except by Mexico. With the aid of exergetic analysis methods, we could identify room of improvement to societies, through sectorial analysis, confirming the hypothesis that, compared to energy analysis, the methodology of exergy analysis is a useful tool since it offers a better and wider approach, an excerpt in accordance to previous scientists (M. A. Rosen, 1992; Utlu & Hepbasli, 2007a).

An analysis of the casual relationship reveals that energy consumption, economic growth and trade openness were the main factors driving the change in CO_2 emissions for the three countries. The huge economic and commerce growth all along these years of study was particularly marked by Mexico, highlighting the marked influence after the NAFTA signing. Significant structural changes in transport, industrial and electricity demand and production are linked to this growing trend affecting CO_2 emissions for data sets (Apergis & Payne, 2010; L. Chen, Yang, & Chen, 2013; Yebing Fang et al., 2017; H. B. Khobai & Le Roux, 2017; Sebri & Ben-Salha, 2014).

Some studies have already attempted to determine the relationship between energy and economic growth among the NAFTA countries. In Mexico, Gomez (Gómez, Ciarreta, &

Zarraga, 2018) in a particular study finds causal links between energy consumption to economic growth; also finds the growth hypothesis; in combined studies; (Bozoklu & Yilanci, 2013)finds temporal causality running from economic growth to energy consumption and finally (Yıldırım, Sukruoglu, & Aslan, 2014) finds support for the neutrality hypothesis.

4.6.2 VAR test

This test combines the traditional VAR approach, treating all the variables in the system as endogenous with the panel data approach, allowing for unobserved individual heterogeneity. Here, similar methodological steps suggested by previous researchers (Magazzino, 2014) were followed.

Once the long-run co-integration and elasticity of the variables were observed, the coefficients of energy consumption and carbon dioxide emissions show statistically significant relationships with economic growth. After testing the proposed alternate variables, it was observed that in respect to the social variable tested, human development index (HDI), a 1% increase may lead to a huge increase in CO_2 emissions (1136%). It shows the influence of the social and economic dimensions of the analyzed countries, and their impacts on the CO_2 emissions, particularly in the case of Mexico. It was interesting to study the HDI variable; particularly with respect to Mexico, since during the 25 studied years, the HDI index increased 11, the biggest compared to the rates of Canada (7) and the USA (6). However, Mexico's HDI by 2015 remains lower than it counterparts, a considerable 16 points mark.

The analysis of the results for Canada shows that a 1% increase in human development index (HDI) may lead to a considerable increase in CO_2 emissions (281%). Then an increase in the economy could affect the environment, increasing considerably the air emissions. In comparison, not as drastic as in Mexico's case, in respect of the DHI variable for the USA, a 1% may lead to a huge decrease in CO_2 emissions (6820%). These results show evidence of the differences in the human development index, putting in perspective two main drivers, pcGDP and population among the three countries.

In respect to the variable exergetic renewable share (ExRS) a 1% increase may lead to a 6.2% decrease in CO_2 emissions. This result points out the need to increase renewable energy sources for Mexico, a great deal from an oil exporter in search of a more balanced and up-today environmentally friendly consumption of energy sources, using fewer fossil fuels and increasing the renewables. Even when this is not statistically significant, has a meaning once the decreasing trend for this variable for Mexico from 1990 to 2014. It shows the need to improve as well as the room for improvement. The Exergetic renewable share variable, shows for the USA interesting results, a 1% increase may lead to a 25.3% decrease in CO_2 emissions, highlighting the relevance and need to increase the use of renewables in this country. For Canada this variable does not show relevant results. In the future, more environmentally acceptable energy sources need to be encouraged and developed. Clean and efficient use of fossil fuels is essential. The development of economic non-fossil sources is also a priority (International Energy Agency (IEA), 2017c).

4.6.3 Granger causality test

Once a long-run relationship among the selected variables was detected, the Granger causality test was applied to determine causal relationships. co-integration among the variables was observed.

Table 4-3 Granger causality test

Mexico	CO_2ff	Encff	GDPpc	FREx	Exint	TRopn	HDI	Direction of Causality
CO_2ff	---	0.0693	0.0414	0.0992	0.2012	0.2939	0.4259	
Encff	0.7961							$CO_2 \leftarrow$ Encff
GDPpc	0.3997							$CO_2 \leftarrow$ GDPpc
FREx	0.8922							$CO_2 \leftarrow$ FREx
Exint	0.7741							
TRopn	0.5366							
HDI	0.2831							
Canada	CO_2 ff	Encff	GDPpc	FREx	Exint	TRopn	HDI	
CO_2 ff	---	0.4437	0.1098	0.8569	0.2023	0.0584	0.1855	
Encff	0.8335							
GDPpc	0.1876							
FREx	0.1965							
Exint	0.1826							
TRopn	0.5053							$CO_2 \leftarrow$ TRopn
HDI	0.3024							
U.S.A.	CO_2 ff	Encff	GDPpc	FREx	Exint	TRopn	HDI	
CO_2 ff	---	0.7356	0.6547	0.0043	0.0324	0.2307	0.7308	
Encff	0.0750							$CO_2 \leftarrow$ Encff
GDPpc	0.0019							$CO_2 \leftarrow$ GDPpc
FREx	0.1825							$CO_2 \leftarrow$ FREx
Exint	0.0070							$CO_2 \leftrightarrow$ Exint
TRopn	0.0132							$CO_2 \rightarrow$ Tropn
HDI	0.1316							

Using time series, it was expected unidirectional or bidirectional causality between the data series in each one of the three countries within an augmented VAR framework following (Toda & Yamamoto, 1995) procedure. It was also tested the proposed exergetic variables as well as trade openness and HDI index. Below, Table 4-3 above, shows the Granger causality results among the variables.

In search of Granger causality, the analysis of Mexico's data, the existence of a unidirectional causality running from CO_2 emissions to economic growth was found;

similarly, a similar behave was observed for the exergetic renewable share and exergy intensity variables.

In addition, searching Granger causality, the most intriguing results arise from the study of the USA; a bi-causal direction was detected between exergy intensity and CO_2 emissions. Also, the existence of unidirectional causality running from several variables (energy consumption, economic growth, exergetic renewable share, and trade openness) to CO_2 emissions was observed.

In respect to the USA, several studies are available; however, applying Granger and VAR methods, it is possible to mention the results of (Soytas, Sari, & Ewing, 2007) finding GDP does not Granger cause CO_2 emissions, but energy use does. Hence, income growth by itself may not become a solution to environmental problems. In 2012 (Franklin & Ruth, 2012) detected EKC in the short run, concluding energy consumption is found to have a negative impact on reducing CO_2 emissions. Dogan results (Dogan & Turkekul, 2016a) does not support the EKC hypothesis; additionally, detected causality running from GDP to energy consumption and also bidirectional Granger causality among CO_2 and GDP, CO_2 and energy consumption and GDP and trade openness while no causality is determined between CO_2 and trade openness.

Contrasting, in the study of Canada, results show just the existence of a unidirectional causality running from CO2 emissions to trade openness. Compared to previous results for Canada, applying Granger and VEC methods, the study of Ghali (Ghali & El-Sakka, 2004) did not find the EKC, only by directional and feedback causality; Results of (He & Richard, 2010), shows little evidence for the EKC, highlighting the relevance of the 1970's oil shock has had on progress towards less polluting technology and production. Recently (Olale et al., 2018) confirmed the EKC hypothesis at Canadian level, however, not at provincial level.

Concerning the test of the EKC hypothesis cited by Apergis (Apergis & Payne, 2009; S.-T. Chen, Kuo, & Chen, 2007), in this study was detected that the GDP – energy (and exergy consumption) confirms the growth hypothesis, similar to GDP-energy consumption correlation results reported by Lee (Lee, 2005) about developing countries. These findings are in the line with (de Janosi & Grayson, 1972; Magazzino, 2011) once energy consumption tends to be more responsive to economic growth in less developed than in advanced countries; however it is important to state that according to them, the relationship between energy and economic growth activity could be affected by a variety of other factors.

Although this is a small sample of three countries, the results of our study could be applied to nations with energy intensive industrial activities. However, in a broader perspective, a country or a society cannot be simplified like this (Ertesvåg, 2001; Gong & Wall, 2016).We are aware that the methods applied to the analysis of the datasets in this research may have limitations. Moreover, when analyses conducted during different periods are utilized to compare worldwide societies, a certain degree of risk remains. In a sense, some societies seem more efficient than others in the use of energy sources.

The worldwide efforts of national governments to commit itself to diminish Climate Change, results in stronger plans and targets to reduce the total emissions of CO_2 by 2050. Around 25-40% reductions in industrialized countries by 2020 from 1990 GHG emissions levels are described as necessary by the Intergovernmental Panel on Climate Change (IPCC) (Höhne et al., 2009). To solve this problem, it is essential to improve the evaluation and reduction of CO_2 emissions of the analyzed countries.

Therefore, the relationship between the consumption of fossil fuels to produce energy and the generation of GHG requires the evolution of environmental and energetic policies concerning a strategic economic activity such as manufacturing, once it includes the three main societal sectors with near 90% of primary energy supply based on fossil fuels, such as the industrial, transformation and transport (S. G. Banerjee et al., 2013). However, changes in energy efficiency and shifts in the fuel mix, especially from carbon-intensive coal to low-carbon gas or from fossil fuels to nuclear or renewable energy, can cut the overall global emissions level

(Jos GI Olivier, Peters, & Janssens-Maenhout, 2012). But, currently due high risks and uncertainty, governments tend to leave the nuclear option as the last resort to produce energy.

A final remark regarding the NAFTA countries analyzed arises. Despite Trump's presidency impasse, however, in near future logic points out to exploit even more this huge North American trade market, with a future population of near 600 million. No doubt, currently and in the future, negotiations regarding the environmental and energetic chapters are key issues. Without a doubt, Mexico's and Canada's geographic positions are privileged in terms of the market, since both countries are neighbourhoods of the USA, one of the largest consumers worldwide. In search of improvement to reduce prices, related to transport -costs-distance-time and simultaneously reduce environmental impacts, proximity is a must.

Eventually, manufacturing will come and go in future scenarios, and then it is imperative for both countries to be ready to satisfy such demands with greener, secure energy scenarios.

4.7 Conclusions and policy implications

The main goal of this article was to examine correlations between economic growth, energy consumption and CO_2 emissions, including how exergetic variables behave. Data sets of three North American countries associated with NAFTA agreement, from years 1990 to 2014, were analyzed in an empirical study.

Results from Canada shows the existence of a unidirectional causality running from CO_2 emissions to trade openness, it is interesting that a similar causality also running from CO_2 emissions to trade openness was observed to the USA, outscoring the relevance for trade among these developed economies.

In search of Granger causality, the results of Mexico's data, reveals the existence of a unidirectional causality running from CO_2 emissions to economic growth; a similar behave was observed for the exergetic renewable share and exergy intensity variables. The most intriguing Granger causal results arise from the study of the USA; a bi-causal direction was detected between exergy intensity and CO_2 emissions. Also, the existence of unidirectional causality running from several variables (energy consumption, economic growth, exergetic renewable share, and trade openness) to CO_2 emissions was observed. Contrasting, in the study of Canada, results show just the existence of a unidirectional causality running from CO_2 emissions to trade openness.

Like previous research, the use of renewables or natural gas seems to be the right way to combat global warming and reduce CO_2 emissions, enabling the reduction of energy dependency and promoting energy security. It is remarkable that restrictions on the use of energy can negatively affect economic growth, while increases in energy can contribute to economic growth. Consequently, it is concluded that energy is a limiting factor for economic growth and, therefore, the impacts on energy supply will have a negative impact on economic growth.

The growth hypothesis of the EKC was confirmed by Mexico: it means that a fall in energy consumption will negatively affect economic growth; negative effects could harm a developing economy. Regardless of results do not hold the EKC hypothesis completely for the three NAFTA countries. However, the exergetic variable opens the door for future research once it proves to be a useful control variable, particularly the exergetic renewable share. According to previous research, it was confirmed that exergy provides opportunities to analyze and implement energy and environmental policies in these countries, once is a tool to minimize environmental harm, with the possibility to link exergy efficiency and the use of renewables.

Regarding future policy implications by NAFTA countries, results could help to increase co-operation to address trans-national threats, supporting inclusive and transparent regulations, codes and even rules, promoting broad public participation mainly from border cities in the task of policymaking. CO_2 emissions are proved to be a regional or international risk to public health, with undesired economic and environmental consequences.

Future research should be focus on applying a more complex econometric model, as well as the inclusion of exergetic variables. Another venue could be focused to develop a deeper analysis of country, provincial or even sectorial scale, regarding the correlations of environmental and exergetic indicators. Finally, one of the main limitations to our study was the availability of data sets, mainly in years before the NAFTA signature.

CHAPTER 5

AN OVERVIEW OF ENERGY AND EXERGY ANALYSIS TO THE INDUSTRIAL SECTOR, A CONTRIBUTION TO SUSTAINABILITY

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Abstract:
Globally, industry remains one of the main consumers of fossil fuels; hence, it is one of the prime sources of greenhouse gases (GHG). Exergy analysis methods can be applied to detect the processes inefficiency. To enhance the interconnection of the exergy and the environment theories, renewable share and exergy efficiency are suggested, in a contribution to sustainability. Exergy analysis is proposed and lifted to study the industrial sector. Even though exergy analysis has been applied to study societies, few studies have been conducted to study emerging-market economies. In 2015, Mexico's crude oil production was the 12th biggest worldwide, therefore fossil fuels are still the main source to produce energy for the domestic and productive sectors of the Mexican society. Consequently, a prospective study case in Mexico is suggested. The sectorial industrial exergy consumption amounts 1350 PJ in 2000, increasing to 1591 PJ in 2015. Both energy and exergy efficiency show similar results along the 16 years, with average energy and exergy efficiency of 78% and 23%, respectively. In comparison with results of similar studies, Mexican exergy efficiency falls within the ranges, yet below the average of 48%. Thus, poor efficiency is still occurring in the sector. Our proposal could provide significant opportunities to become a more sustainable sector, based on the exergetic renewable share and the exergy efficiency.

Keywords: climate change; energy; exergy analysis; greenhouse gases; industrial sector; Mexico; exergetic renewable share; sustainability

5.1 Introduction

Nowadays, the rates of worldwide economic development indicate that increased energy demand at all sectoral levels may represent a threat to the achievement of global reduction objectives for 2050 [(Intergovernmental Panel on Climate Change (IPCC) UNEP, 2016). The industrial sector plays a key role in terms of energy use and air emissions. Characterized by easy dispersion, persistence over time and historic load, industrial atmospheric pollution from fossil fuels is the third-largest source of global warming (US-Environmental protection Agency (US-EPA), 2016). The growing consumption trends of the industrial sector, which remains the main source of energy worldwide, and rising concerns in terms of energy supply security make the prevention of the consumption of fossil fuels extremely relevant(Sadorsky, 2009). Since the early 1970s, environmental assessment and tools derived from it has been developed to decrease the danger of industrial activities. Conventional environmental impact evaluation methodologies, however, have shown relative effectiveness. In addition, several environmental measures have been implemented since the 1990s.

In parallel, after the 1973 oil embargo, the first studies of exergy were developed focusing on energy savings when governmental agencies of industrialized countries were forced to study exergy in a deeper way (Moran & Sciubba, 1994). Exergy can be used to detect the inefficiencies of a process by locating the degradation of energy. Availability or exergy was defined by Reistad as “the thermodynamic property that measures the potential of a system to do work when restricted by the inevitable surroundings and Po (dead state temperature and pressure)” (G. Reistad, 1975a). Recently, Boroumandjazi defines exergy as “the maximum amount of work that can be produced by a system or a flow of matter or energy in equilibrium with its surroundings” (BoroumandJazi et al., 2013). Since the late 1970s, towards the late 1990s, researchers such as Rosen, Dincer and others, have been working in the field of exergy accounting and exergy societies (Marc A. Rosen & Dincer, 2001; Göran Wall, 1977a).

In parallel, exergy analysis was also studied regarding the environment and sustainability (Dincer & Rosen, 2004; M. A. Rosen, - Dincer, Ibrahim, 1997; Marc A. Rosen & Dincer, 2001). In 2007, Sciubba summarized the evolution of exergy (Enrico Sciubba & Wall, 2007) since the first theoretical developments of Reistad (G. Reistad, 1975b), as a concept to resource accounting (Jan Szargut et al., 1987; Göran Wall, 1977a), energy conservations (Van Gool, 1980), efficiency improvements in industrial equipment or power cycles and its components (Lozano & Valero, 1987), environmental applications (Dincer & Rosen, 2012; Marc A. Rosen & Dincer, 2001; Marc A Rosen et al., 2008), complex systems analysis (Milia & Sciubba, 2006; Enrico Sciubba et al., 2008), sectors and extended exergy analysis in societies or countries (Ayres et al., 2003; G. Chen & Chen, 2009; Swan & Ugursal, 2009; Göran Wall, 1990; Göran Wall et al., 1994), mainly including conversion, transportation, residential and agricultural sectors (Ertesvåg, 2001; M. A. Rosen, 1992).

The available evidence seems to suggest that exergy efficiencies are more suitable to evaluate systems and detect areas in need of improvement, even those on a large scale such as the economic sectors of a country or an entire society. Gong established that "to improve energy and material conversion processes, the exergy concept should be applied. Thus, exergy and exergy analysis are necessary tools to create and maintain a sustainable or rather a vital society" (Gong & Wall, 2016). Researchers also claim that exergy brings opportunities in decision-making to increase energy efficiency (Enrico Sciubba et al., 2008) and energy conservation (Utlu & Hepbasli, 2009). Exergy analysis has been developed in the industry covering three fundamental categorizations: by sector, by type of industry and by equipment.

Qualitative research has been conducted in the field of exergy to study the industrial sector (Bligh & Ugursal, 2012; BoroumandJazi et al., 2013; Gong, 2005; Kotas, 2013; Michaelis, Jackson, & Clift, 1998; Oladiran & Meyer, 2007; Marc A Rosen, 2013; Saidur, Abdul Khaliq, & Masjuki, 2006; Sanaei, Furubayashi, & Nakata, 2012; Jan Szargut et al., 1987; Utlu & Hepbasli, 2007b; B. Zhang et al., 2012), but there have been few studies in developing countries or emerging economies. According to the World Bank, to pay attention to the economical–social–environmental challenges of the future, the upper-middle-income countries need to be assessed deeply. In the case of Mexico, exergy analyses are scarce, mainly by its economic or social sectors (García Kerdan, Morillón Gálvez, Raslan, & Ruyssevelt, 2015; Guevara et al., 2016; Rivero, Rendón, & Gallegos, 2004). Energy analysis has been widely used by academics and Mexican government agencies. However, it needs to be employed with care due its limitations as criteria to assess energy-related projects. Thus, Hammond (Hammond & Stapleton, 2001) has argued that it is important to employ exergy analysis based as a complement to the existing methods to develop official reports and environmental and energetic strategies.

Little is known about the Mexican society and its industrial sector despite its relevance due to its growing market and its strategic geographic location in between North and South America. The aim of this work is to explore the energy and exergy consumption rates as well as the changes of the efficiency of energy (η) and exergy (ψ) utilization of the industrial sector to detect areas in need of improvement. Additionally, exergetic renewable share and exergy efficiency are computed and then proposed as sustainability indicators with the goal to enhance the interconnection of the exergy concept with environmental issues. A study case was performed over the period from 2000 to 2015 over the industrial sector energy consumption data, thus addressing the gap about the Mexican Industrial Sector (MIS). These improvements could potentially provide significant opportunities for energy savings, withstand by the exergetic renewable share and exergy efficiency, and, in this manner, determine to what extent the resource supply is renewable, and, in effect, more sustainable.

5.2 Methodology

This section describes the useful exergy analysis accounting methodology applied to develop energy and exergy analysis of the industrial sector. A case study in Mexico, over the period from 2000 to 2015, was developed. The necessary statistical data have been taken from the Mexican official reports of SENER (National Minister of Energy) from 2010 to 2015. To complete the research data, statistics from IEA (International Energy Agency) website were analyzed. Total final consumption of energy and exergy were analyzed. The thermodynamic energy and exergy efficiencies of the industrial sector were computed. Besides, the exergetic renewable share was analyzed, and proposed jointly with the exergy efficiency as indicators of sustainability. Finally, a comparison with other countries was established.

In some respects, the current work is analogous to the energy and exergy analysis to assess the energy utilization efficiency in the Turkish industrial sector performed by Utlu in 2007 as part of a newer study based on the approach of Reistad in 1975 and the previous work of Rosen in Canada in 1992. This energy strategy for Canada and Turkey had a great influence on energy planning elsewhere in the industrialized world. This study draws on research conducted by Rosen (M. A. Rosen, 1992) and Utlu (Utlu & Hepbasli, 2007a). A proposal to update the exergy analysis method applied to the industrial sector was completed, thus process heating temperatures, electricity and fossil fuels efficiencies were modified, in the assessment of energy and exergy efficiencies

5.2.1 Theoretical Background

Previously, scholars have been studying exergetic techniques on a large-scale. Dincer (M. Rosen & I. Dincer, 1997) evaluated the energy consumption of the industrial sector in Turkey to increase its efficiency based on exergetic analyses. To formulate an exergy balance of a non-constant flow system (similar to mass or energy balances), a common scenario requires establishing a control volume as well as a reference environment; it is usually established through a temperature T_0 = 25 °C and a P_0 =1 atm. (Dincer & Rosen, 2013b). The flow of exergy entering in a system can be best described as the sum of the totality of their exergies (physical, chemical, potential, kinetic and nuclear exergies) (Marc A. Rosen, 2013):

$$Exergy\left(\frac{kj}{kg}\right) = Exergy_{physic} + Exergy_{kinetic} + Exergy_{potential} + Exergy_{chemical} + Exergy_{nuclear} \tag{5.1}$$

If the components linked to the potential, kinetic and thermodynamic exergy are equal to zero in the system, then Equation (1) can be simplified as:

$$Exergy\left(\frac{kj}{kg}\right) \cong Exergy_{chemical} \tag{5.2}$$

If a reversible process is carried out, then the exergy is conserved, otherwise, in an irreversible process, the exergy is always lost or degraded. It can be expressed as the subtraction between the exergy input and the exergy output from the whole system. Therefore, the general equation of the exergy balance is then expressed as:

$$\sum Exergy\ ouput - \sum Exergy\ \ input\ = \sum Exergy\ loss \tag{5.3}$$

In large-scale exergy analyses, the flows of energy mainly include fossil fuels operating at standard conditions of temperature and pressure (25 °C and 1 atm., respectively). The specific chemical exergy of fuels in reference conditions of temperature and pressure (T_0 and P_0) are usually close or equal to its high heating value (HHV). Therefore, the physical exergy for these flows equals zero. Accordingly, if the total exergy consists of physical and chemical exergies, it is reduced to only the chemical exergy values (Equation (4.4).

$$Exergy\left(\frac{kj}{kg}\right) \cong Exergy_{Chemical} \cong HHV \tag{5.4}$$

Examples of the most common values are shown in Table 5-1 (Marc A. Rosen, 2013; Utlu & Hepbasli, 2007a). To acquire the values for the Mexican mixture of crude oil, a combination of 50%/50% (by volume) was considered (Rivero, Rendon, & Monroy, 1999). Then, the quality factors to convert energy to exergy values are determined by Equation (4.5).

$$\gamma = \frac{Exergy_{Chemical}}{HHV} \tag{5.5}$$

Table 5-1 Properties of the most common energy sources.
Adapted from (M. A. Rosen, 1992; Utlu & Hepbasli, 2007a)

Energy Carrier	High Heating Value (HHV) (kJ/kg)	Chemical Exergy (kJ/kg)	Quality Factor (Dimensional) γ
Coal	32,733	34,090	1.04
Gasoline	47,849	47,394	0.99
Fuel Oil	47,405	47,101	0.99
Natural Gas	55,448	51,702	0.93
Crude oil (Mexican Mixture)	42,414	44,800	0.94
LPG	45,460	45,005	0.99
Electricity	3600.6	3600.6	1.00

5.2.2 Computation of the Thermodynamic Efficiencies: Energy (η) and Exergy (ψ)

Previous studies applied different equations to obtain thermodynamic efficiencies to evaluate the control volume (Aljundi, 2009; Moran & Sciubba, 1994; Ozcan & Dincer, 2013; Tsatsaronis, 2007). Energy and exergy heating efficiencies derive from the first and second laws of thermodynamics, respectively. Electric and fossil fuel heating processes were chosen to generate products heat *Qp* at a *Tp* (constant temperature) either from electrical energy We or fuel mass *mf*. Then, the efficiency of electrical and fuel heating are (Utlu & Hepbasli, 2007b):

$$\psi_{e,h=}\left[\left(1-\frac{T_0}{T_p}\right)\eta_{e,h}\right] \tag{5.6}$$

$$\psi_{f,h=}\left[\left(1-\frac{T_0}{T_p}\right)\eta_{f,h}\right] \tag{5.7}$$

Where T_0 = 298 K, Low T_p = 315 K, Medium T_p = 414 K and High T_p = 859 K. Then, to compute the electric heating efficiencies, the following equations were applied:

$$\psi_{f,h} = Ex^{Qp}/m_f\psi_f \tag{5.8}$$

$$\psi_{f,h=}\left[\left(1-\frac{T_0}{T_p}\right)Q_p\right]/\left(m_f\gamma_f H_f\right) \tag{5.9}$$

The diversity and complexity characteristics of the industrial sector make the assessment of the accurate conditions of each process (temperature, pressure, thermodynamic properties, etc.) nearly unmanageable. In this paper, we propose to apply some differences to process heating temperatures, and electricity and fossil fuel efficiency, according to the up-to-date conditions of the industrial sector.

Essentially, the changes applied to Table 5-2 were the following: increasing Mean T_p by all sectors; raising the high range Electrical Heating η (%) from 70 to 75 and increasing the three ranges of Fuel Heating efficiency (%) to 70, 85 and 100 (Hammond & Stapleton, 2001).

To compute the energy and exergy efficiencies shown in Table 5-3, an extensive investigation was developed to find wider criteria and data of industrial end-use heating temperatures from different manufacturing activities (R. Banerjee et al., 2012; Bühler et al., 2016; US-Department of Energy (US-DOE), 2015; Vannoni, Battisti, & Drigo, 2008). We utilized the data from Table 4.2 and the quality factors from Table 5-1.

Process heating operations are the source of thermal energy to transform materials such as metal, plastic, rubber, limestone, etc., into a wide variety of industrial products. Process heating operations are mainly utilized to raise or maintain the temperature of substances involved in the manufacturing process. Industrial heating processes include drying, heat-treating, calcining, smelting, etc.

Examples of process heating systems include furnaces, ovens, dryers, heaters, and kilns. Process heating accounts for nearly 70% of all the process energy (energy applied to convert material into manufactured products) used in the U.S. manufacturing sector (US-Department of Energy (US-DOE), 2015). Figure 4-1 shows that the MIS manufacturing process energy (fuel and electricity used on site at industrial facilities) rounded to 1601 PJ in 2015 with an estimated value of 75% energy sources used just for process heating. Values for U.S. Manufacturing in 2010 rounds to 70% of energy used for process heating, and those of Turkey in 2003 were 78% (US-Department of Energy (US-DOE), 2015; Utlu & Hepbasli, 2007a).

Table 5-2 Data heating processes for industrial activities, adapted from Utlu (Utlu & Hepbasli, 2007a)

		Process heating data (*Tp* range, energy and exergy efficiencies)				**Breakdown of energy and exergy efficiencies for each *Tp* category**			
						Electrical heating		**Fuel heating**	
Industrial Subsectors	**Manufacturing operation applications**	***Tp* range**	**Mean *Tp*(◦*C*)**	**Electricity *(%)***	**Fuel *(%)***	***η e,h (%)***	***ψ e,h (%)***	***η f,h (%)***	***ψ f,h, (%)***
Iron-Steel	Coking	Low	190	4.2	0	100	6.3	100	4.1
	Calcining	Med	300	0	0	90	-	85	-
	Smelting & metal melting	High	1650	95.8	100	75	53.4	70	38.1
Chemical	Drying	Low	60	62.5	0	100	5.4	100	3.5
	Other heating	Med	300	37.5	100	90	25.2	85	16.8
	Fluid heating	High	600	0	0	75	42.8	70	30.6
Cement	Pre-heating	Low	60	91.7	0.9	100	5.4	100	3.5
	Calcining	Med	500	0	9.0	90	25.2	85	16.8
	Sintering	High	1500	8.3	90.1	75	45.7	70	32.7
Sugar	Mingling- centrifuging	Low	65	100	59.0	100	16.3	100	10.6
	Filtering	Med	315	0	9.0	90	44.4	85	29.6
	Evaporation	High	400	0	32.0	75	39.0	70	27.9
Mining and non-iron metals	Crushing	Low	60	10	13.8	100	10.8	100	7.0
	Grinding	Med	150	9.4	22.6	90	23.8	85	15.9
	Separation; tickening; refining	High	500	80.4	63.6	75	39.1	70	27.9
Other manufacturing	Pre-heating	Low	60	10.6	13.8	100	9.7	100	6.3
	Fluid Heating	Med	460	89.4	86.2	90	23.8	85	15.9
	Other heating	High	600	0.1	0.1	75	39.0	70	27.9

Table 5-3 MIS thermodynamic efficiency results: energy (η) and exergy (ψ), 2000–2015

		Process heating data (T_p Range, Energy and Exergy Efficiencies)				Breakdown of energy and exergy efficiencies for each T_p category				Energy-Exergy efficiencies		Energy-Exergy efficiencies	
						Electrical heating		Fuel heating		Electrical heating		Fuel heating	
Industrial subsectors	**Manufacturing operation applications**	***T_p range***	**Mean T_p (°C)**	**Electricity** (%)	**Fuel** (%)	$\eta_{e,h}$ (%)	$\psi_{e,h}$	$\eta_{f,h}$ (%)	$\psi_{f,h}$	$\eta_{e,h}$ (%)	$\psi_{e,h}$	$\eta_{f,h}$ (%)	$\psi_{f,h}$
Iron-Steel	Coking	Low	190	4.2	0	100	6.3	100	4.1				
	Calcining	Med	300	0	0	90		85	-	75.3	51.4	70.0	38.1
	Smelting and metal melting	High	1650	95.8	100	75	53.4	70	38.1				
Chemical	Drying	Low	60	62.5	0	100	5.4	100	3.5				
	Other heating	Med	300	37.5	100	90	25.2	85	16.8	62.8	3.4	85.0	16.8
	Fluid heating	High	600	0.0	0	75	42.8	70	30.6				
Cement	Pre-heating	Low	60	91.7	0.9	100	5.4	100	3.5				
	Calcining	Med	500	0	9.0	90	25.2	85	16.8	97.0	8.7	71.6	31.0
	Sintering	High	1500	8.3	90.1	75	45.7	70	32.7				
Sugar	Mingling; centrifuging	Low	65	100	59.0	100	16.3	100	10.6				
	Filtering	Med	315	0	9.0	90	44.4	85	29.6	93.8	16.3	89.1	17.8
	Evaporation	High	400	0	32.0	75	39.0	70	27.9				
Mining and non-iron metals	Crushing	Low	60	10.0	13.8	100	10.8	100	7.0				
	Grinding	Med	150	9.4	22.6	90	23.8	85	15.9	70.3	32.5	77.5	22.3
	Separation; refining, etc.	High	500	80.4	63.6	75	39.1	70	27.9				
Other manufacturing	Pre-heating	Low	60	10.6	13.8	100	9.7	100	6.3				
	Fluid Heating	Med	460	89.4	86.2	90	23.8	85	15.9	10.7	1.1	87.1	14.6
	Other heating	High	600	0.1	0.1	75	39.0	70	27.9				

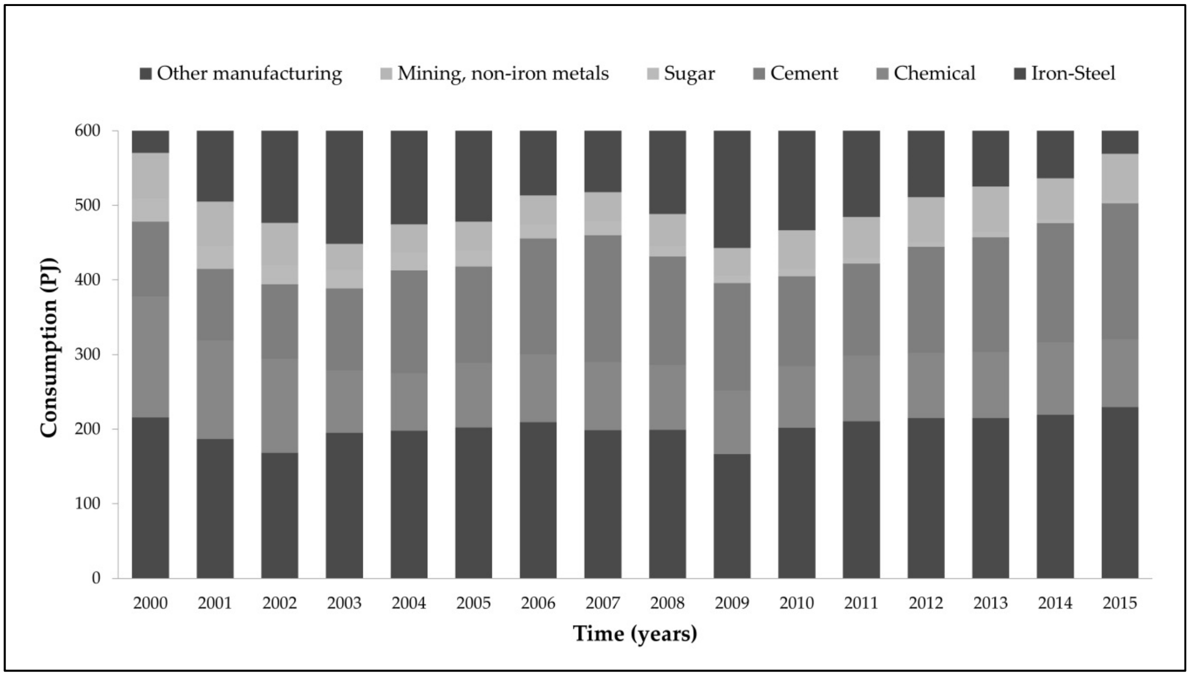

Figure 5-1 MIS energy consumption rates, 2000-2015

This work subdivides energy for process heating technologies based on the type of fuel consumed into two categories: fossil fuel and electric systems. Starting from the database of the processes, electrical heating, fuel heating, and heating efficiencies were computed (Table 5-2). The energetic and exergetic efficiencies were calculated by Equations (4.5) and (4.6). Comparing the electrical and heating efficiencies to those of fossil fuels, previous studies stated that the electrical efficiencies are mostly higher. Consequently, their process heating values are the highest (100-90-70 for High-Med-Low heating). To handle and analyze the performance of industrial activities based on the first and second laws of thermodynamics correctly, previous researchers have established approaches specifically designed for these scenarios (BoroumandJazi et al., 2013). The following restrictions were established to simplify the scope of this study:

(1) Only the heating and mechanical sub-processes inside the facilities were considered once they were around 95% of the industrial energy uses.

(2) Since fossil fuels and electricity were considered the sources with highest consumption rates inside the industrial plants (97.65% in MIS, 2015) (Energia., 2015), they

were employed as the two main sources of energy carriers. In accordance with Utlu's methodology (Utlu & Hepbasli, 2007a), standard reference operation conditions of the industrial activities were divided into three different categories of Temperature Heating (TH) in terms of heating processes temperatures (Low (LTH), Medium (MTH), and High (HTH)) to be assessed. Table 5-2 summarizes the conditions and computing of the main methodological steps.

5.2.3 Computation of the exergetic renewable share (ERS)

Once the exergetic renewable share is proposed as a sustainability indicator, it could be defined by means of the ratio of the renewable sources of the exergy fraction divided by the total amount of exergy consumed by the system, expressed in terms of percent (Gong & Wall, 2016). According to Gong and Wall (Gong & Wall, 2001), both exergy efficiency and exergetic renewable share can be considered indicators of the sustainability of a system. Since they embody a relation of energy consumption or exergy in comparable units (PJ, ktoe, etc.), they are therefore dimensionally expressed in terms of the percentage (%). Gong defines the renewable fraction as "the fraction of resources that has a source of renewable energy among the total resources consumed in the system".

The development of exergy based indicators shows a relevant role in search of sustainable societies (Koroneos, Nanaki, & Xydis, 2012). Agreeing with Dincer, Rosen, Haselli, et al., our proposal in this paper is based on the approach that, once exergy efficiency tends to increase, environmental impacts (air emissions) conversely decrease, and thereafter sustainability will increase (Ao, Gunnewiek, & Rosen, 2008; Dincer, 2000; Dincer & Rosen, 2004; Haseli, Dincer, & Naterer, 2008; Marc A. Rosen & Dincer, 2001; Marc A Rosen et al., 2008). One of the reasons behind the computation and comparison of the exergetic renewable share with the exergy efficiency in our study case was to observe their performance. While searching for the renewable share analysis of the MIS, due to the lack of reliable data sources, the previously quoted five SENER reports' databases were analyzed to be consistent with the computed overall exergy efficiencies.

5.3 Study Case

5.3.1 Mexico; economic, energetic and environmental issues of the industrial sector

Mexico is a developing country, with a population of around 126 million inhabitants in 2015, living in nearly 2,300,000 km2 (The World Bank, 2017). Its economy is the second largest in Latin America and the 15th largest in the world. Since 1994, it belongs to the Organization for Economic Co-operation and Development (OECD) and the North American Free Trade Agreement (NAFTA). The positive effect of these two keystones allows a constant economic growth (Organisation for Economic Co-operation and Development (OECD), 2013). Between 2000 to 2014, the MIS averaged 35% of Mexico's GDP. In terms of oil power, in 2015, Mexico was the world's tenth major producer of oil and holds approximately 11.1 billion barrels of oil reserves. Mexico remains as one of the ten non-Organization of Petroleum Exporting Countries (non-OPEC) major producers of oil, and has been for the last four decades (International Energy Agency (IEA), 2008a; US-Congressional Research Service, 2015).

Consequently, it is one of 20 countries with the highest global index of GHG production (Sheinbaum-Pardo, Mora-Pérez, & Robles-Morales, 2012), since fossil fuels are still the major source of energy production for the domestic and productive sectors of the Mexican society. According to the energy ministry (SENER), the industrial sector is the second-largest consumer of energy, preceded only by the transportation and followed by the residential–commercial and agricultural sectors. In 2015, the MIS reached 32% of the total national consumption, a growth of 3.3% with respect to the previous year. Nearly 50% of the total consumption corresponds to the manufacturing industry. However, its environmental problems are also increasing (David I Stern, 2007).

Several studies report that the eco-performance of the MIS is unsatisfactory with limited and unrealistic goals and policies (Tracker, 2015). In terms of CO_2 generation, at sectorial level, MIS was the third bigger contributor, preceded just by the Conversion (35.1%) and Transportation (34%) sectors in 2015. These sectors account for nearly 90% of the total amount of CO_2 generation in Mexico (Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT), 2013b). There are ten main industrial and commercial corridors, where the highest-polluting sources are located (Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT), 2017).

The Mexican government committed itself through the Special Climate Change Plan (PECC) to a goal of 50% reduction in the total emissions of CO_2 by 2050. The industrial sector is a key player to achieve the goal to reduce 202 of the country 973 Mt CO_2 eq by 2030 (Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT), 2013a). To solve this problem, it is essential to contribute to and improve the evaluation and reduction of GHG production of the MIS. Therefore, the relationship between the consumption of fossil fuels to produce energy and the generation of GHG requires the evolution of environmental and energetic policies concerning a strategic economic player such as the industry.

5.3.2 Data sources

According to the International Energy Agency (IEA) reports, data from Mexico are available from 1971 onwards, although the Mexican authorities submitted data to IEA for the first time in 1992. Since then, they are frequently reviewed and projected for the previous years (International Energy Agency (IEA), 2016b). Therefore, statistics were selected from Mexican official reports (Energia., 2015; Energıa., 2010; Secretaria de Energia (SENER) Mexico, 2012, 2016; Secretaria de Medio Ambiente y Recursos Naturales (SEMARNAT), 2013a), even though reliable statistics between 1990 and 2000 are hard to find, and tend to be inaccurate (Instituto Nacional de Estadística, 2001, 2010; International Energy Agency (IEA), 2016a). Due to the lack of reliability, a shorter version and more reliable dataset was selected for the period from 2000 to 2015, also from the IEA website.

However, some breaks in the time series may occur and the values of SENER compared with those of IEA may differ significantly. Then, in this study, databases from SENER were analyzed once they reflected the whole sector and all the sub-activities for the sixteen-year gap. Considering their patterns of consumption and their relevance to the industry in economic and social development, five of the main branches selected in the study are high energy-intensive industries (HEII) consumers. They encompass around 38% of the MIS in 2015 (Secretaria de Energia (SENER) Mexico, 2016). Figure 5.2 describes the Mexican Society Sectors, their whole interactions and the breakdown of the industrial activities (shaded components) reviewed in this paper.

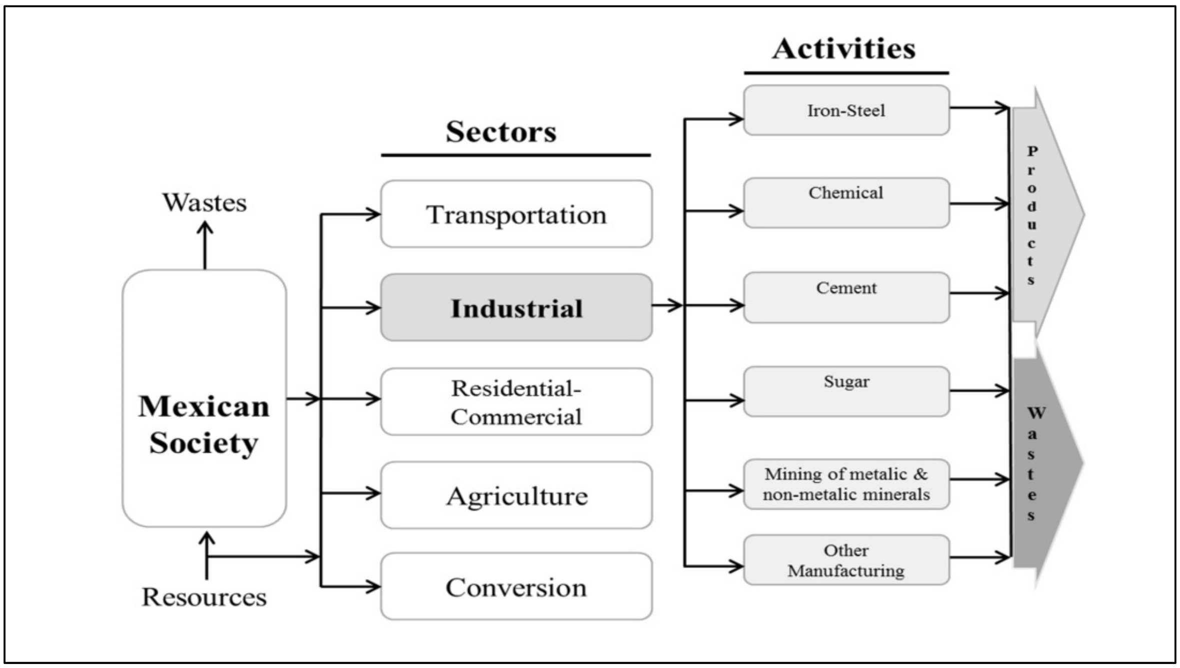

Figure 5-2 Mexican Society Sectors, 2015

The remaining industrial subsectors (contained within the other manufacturing activity) include nine types of manufacturing: glass manufacturing, pulp and paper, alcoholic and non-alcoholic beverages, automotive, etc. (Instituto Nacional de Estadística, 2010).

5.4 Results

5.4.1 Mexican Industrial Sector (MIS) exergy consumption

Figure 5-1 shows the results of exergy input consumption (PJ) for the period under study considering fossil fuels and electricity as the two main sources of energy. Consumption of exergy during the whole period shows a general increasing pattern, from 1350 PJ in 2000 to 1591 PJ in 2015. By subsectors, the same increasing trend was depicted, except for the sugar subsector with an extreme decrease of 86% of exergy consumption. This trend is similar to the energy consumption reported by SENER, since they keep a direct proportion of the energy inputs and the quality factors expressed in Table 5-1. Regarding its evolution along the 16-year span, a marked downward variation between 2009 and 2010 is observed in two subsectors: iron and steel and Cement.

5.4.2 Mexican Industrial Sector (MIS): energy (η) and exergy (ψ) efficiencies

Both efficiencies were computed from the data obtained and shown in Table 5-3. After we applied the changes to the method, overall energy efficiency η values were higher for all the activities, even higher than those previously reported by Utlu in 2007; among the six activities and over the 16 years of the study for the SIM, results ranged from 67% to 92%, with an overall average of 78%. On the other side, exergy efficiencies (ψ) shows lower results, from 11.08% to 38.59% and an overall average of 22.78%. Once the values of η and ψ efficiencies were computed, the results displayed steady and similar trends of increasing or decreasing along the 16-year spam. Individually, the sugar industry portrayed the biggest η (90.4% overall) and the iron and steel industry the biggest ψ (39.02% overall). In these results, it highlights that according to SENER reports (Energia., 2015; Secretaria de Energia (SENER) Mexico, 2016), the iron and steel industry shows the highest ψ due the employment of electric arc furnaces. In contrast, and the sugar sector displays the major η essentially due the usage of cane bagasse as an alternate fuel (a renewable source)

5.4.3 Mexican Industrial Sector (MIS) Exergetic Renewable Share (ERS)

During the period of study, the consumption trend of renewable sources of energy in Mexico shows a remarkable 40% decrease during the 16-year spanned. The trend decreases from 62 PJ in 2000 to 37.4 PJ in 2015. The main source was biofuels and waste, primarily provided by the industry of sugar as cane bagasse. In addition, this subsector was the major consumer of cane bagasse once it was an important by-product of its own manufacturing processes.

Table 5-4 depicts the decreasing trend during the whole span with an interesting 48% exergetic renewable share decrease during the period of 16 years. The final consumption by the industrial sector of solar and geothermal energy accounts for just 0.46 PJ in 2015, a number that reflects how hard the Mexican industry needs to work to improve its renewable share. The final consumption as a country for all sectors accounts for a small 9 PJ in 2015.

Table 5-4 MIS evolution of the exergetic renewable share, from 2000 to 2015

Time (Years)	Exergetic Ren. Resources MIS (PJ) (Average)	Exergetic Ren. Share (%)	Time (Years)	Exergetic Ren. Resources MIS (PJ) (Average)	Exergetic Ren. Share (%)
2000	62.0	4.6	2008	63.8	4.5
2001	72.2	5.9	2009	54.3	4.2
2002	70.4	5.6	2010	50.6	3.6
2003	57.1	4.5	2011	45.7	3.0
2004	56.9	4.3	2012	44.9	3.0
2005	69.9	5.2	2013	64.8	4.1
2006	62.3	4.3	2014	38.8	2.5
2007	64.0	4.5	2015	37.4	2.4

5.5 Discussion

5.5.1 Approach to Update the Exergy Analysis Method Applied to the Industrial Sector: Case Study Application

In this paper, we propose to apply some differences to process heating temperatures and efficiencies according to the up-to-date conditions of the industrial sector. Essentially, we focused our attention on Table 5-2, modifying process heating data: increasing Mean Tp by all sectors except sugar; raising the high range electrical heating η from 70% to 75%; and growing three ranges of fuel heating η, from 70%, 85% and 100%. After testing changes to observe their influence on the computing of energy and exergy efficiencies, results show a slight increasing tendency. It is interesting to note that, even though several authors have studied societal sectors, few of them (BoroumandJazi et al., 2013; Dincer, Hussain, & Al-Zaharnah, 2003; Marc A Rosen, 2013; Utlu & Hepbasli, 2007a) have shown details of their methodological steps to developed exergy analysis to the industrial sector, and dissected the complete sector by subsectors.

Contrasting our results computed and shown in Table 5-3 with those of Utlu in 2007, highlights the influence of the proposed modifications (to the processes heating temperature and the electrical and fossil fuel heating efficiencies to compute the overall energy efficiency), resulting in an overall 10% to 20% energy efficiencies, higher than Utlus's results. The main trend among both efficiencies is generally similar for both studies.

In 2013, BoroumandJazi quoted values between 12.95% and 18.52% for mining (and quarrying), compared to 25.69% and 28.61% for the MIS. He also refers to Iranian industrial sector results of around 63% and 42% for both efficiencies, contrasting with 78% and 23% for the MIS. Rosen summarizes just a few of them, referring to values for both efficiencies in the overall industrial sector (51% and 30%) as well as for iron and steel (52% and 27%), chemical (57% and 32%) and mining (54% and 35%) subsectors. Compared with the MIS results, some similarities were observed in terms of η, as well as differences, e.g. in ψ, with bigger results than MIS.

Concerning previous studies for Mexico, in 2014 Garcia (García Kerdan et al., 2015) in his analysis of the Mexican non-domestic sector find that his results of exergy efficiency were the highest (19.7% overall) after a comparison with other countries. In 2016 Guevara (Guevara et al., 2016) analyzed the useful exergy and the energy transitions of Mexico, observing the strong dependency of the Mexican economy on fossil fuels (oil and natural gas), and points out that the renewable resources reduced their share by 50% while electricity gained relevance between 1971 and 2000. Guevara highlights the lowest automation of the Mexican industry, once Mexico still more labor-intensive compared with developed countries.

5.5.2 Mexican Industrial Sector: energy and exergy consumptions and efficiencies

After 1994, Mexico's growing scenario started with an expansion of the anchor industrial sub-sectors, as a consequence of foreign investments. Despite global efforts to improve energy efficiency, the industrial sector remains one of the main consumers of fossil fuels with global numbers from 30% to 70% (Abdelaziz, Saidur, & Mekhilef, 2011; Dincer &

Rosen, 2012) of the total consumption. This confirms the growing trend of energy consumption of the MIS results during the analyzed period of 16 years (18.6 % by the MIS, 10.2 % for fossil fuels), with maximum rates in 2015 for fossil fuels. By 2015, in the whole sector, iron-and-steel production (210 PJ) and cement industries (147 PJ) were the largest consumers of fossil-fuels. Just five of the main activities consumed 45% of the 1024.2 PJ used by the MIS.

A descriptive analysis was developed to observe the behavior of both efficiencies. Figure 5-3 summarizes the differences in the dispersion values when comparing them. Figure 5-3a shows the results of the exergy efficiencies, a narrow dispersion characterizes the results from the MIS and four of the subsectors (iron and steel, chemical, sugar and mining). From a contrasting point, dispersed values belong to two subsectors: cement and other manufacturing.

It highlights the other manufacturing industrial activities displaying the lowest average values of exergy efficiency than the other subsectors (11.8%), mainly due to the diverse and wide range of activities utilizing energy sources with low levels of HHV. Figure 5-3b shows the results of the energy efficiencies. Here, narrow dispersion characterizes the results of three of the subsectors (iron and steel, chemical, and mining) and the MIS. Conversely, dispersed values belong to three subsectors: cement, sugar and other manufacturing. It highlights the sugar industry displaying the highest average values of energy efficiency of all subsectors (90.5%).

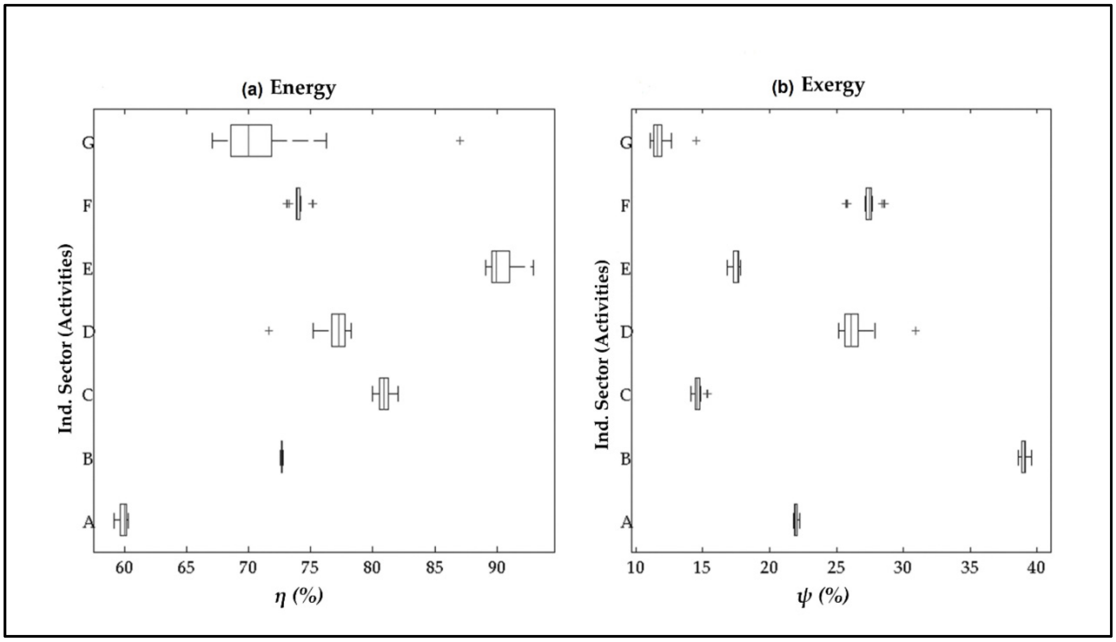

Figure 5-3 MIS average values of thermodynamic efficiencies, 2000–2015: (A) SIM Total; (B) Iron and Steel; (C) Cement; (D) Chemicals; (E) Sugars; (F) Mining of non-metallic minerals; and (G) other manufacturing. (a): Energy efficiency (η); (b)Exergy efficiency (ψ)

To observe the MIS performance in terms of energy inputs, differences were detected in terms of increasing or decreasing values of energy or exergy efficiencies during the 16-year spanned, comparing the extreme years (2000 vs. 2015). In summary, we can claim that we observe remarkable differences for both efficiencies. In terms of energy, we can observe that the overall value for the MIS decreases 0.35%. Contrarily, we detected decreasing consumptions in the remaining five of the six subsectors with results no bigger than 1.5%. To summarize, both efficiencies behave similarly, with constant trends of increasing and decreasing peaks generally no bigger than 2% or 3% (exceptionally, 4%) along the entire 16-year span. Consequently, areas in need of improvement were detected to confirm one of the main goals of this research.

We consider there are different reasons behind this behavior: technological improvement, raw materials, good environmental practices, and, mainly, the type of fuel (M. A. Rosen, 1992). In summary, the most noteworthy differences between energy and exergy efficiencies are mainly attributable to heating processes. High heating efficiencies must be used to bring high end-use demands; however, the opposite occurs. It suggests areas in need of improvement for most of the subsectors. Consequently, the overall exergy efficiency of the sugar subsector is significantly lower (17.6%) than the overall energy efficiency (67.31%).

5.5.3 Mexican Industrial Sector (MIS): thermodynamic efficiencies comparison to detect areas in need of improvement

The exergy analysis (2000–2015) displayed some considerable differences between the overall energy and exergy efficiencies in the Mexican Industrial Sector. This disproportion indicates available energy losses, which could be a factor of sectorial inefficiency, and, consequently, areas in need of improvement. Focused on the differences between the results of the overall energy and exergy efficiencies, we could establish that there is potential for energy optimization, since the exergetic efficiency identifies the irreversibility of the system under study (Kondo, 2009). Figure 5-4 is a sample illustration of the year 2015. It depicts differences between the computed statistic median thermodynamic efficiencies for the whole sector. The iron and steel industry shows the lowest gap (33%), in contrast to the sugar industry (76%), the chemical industry (66%) and the other manufacturing industries (60%). These results can be based on the slight differences among the energy sources used by each sector.

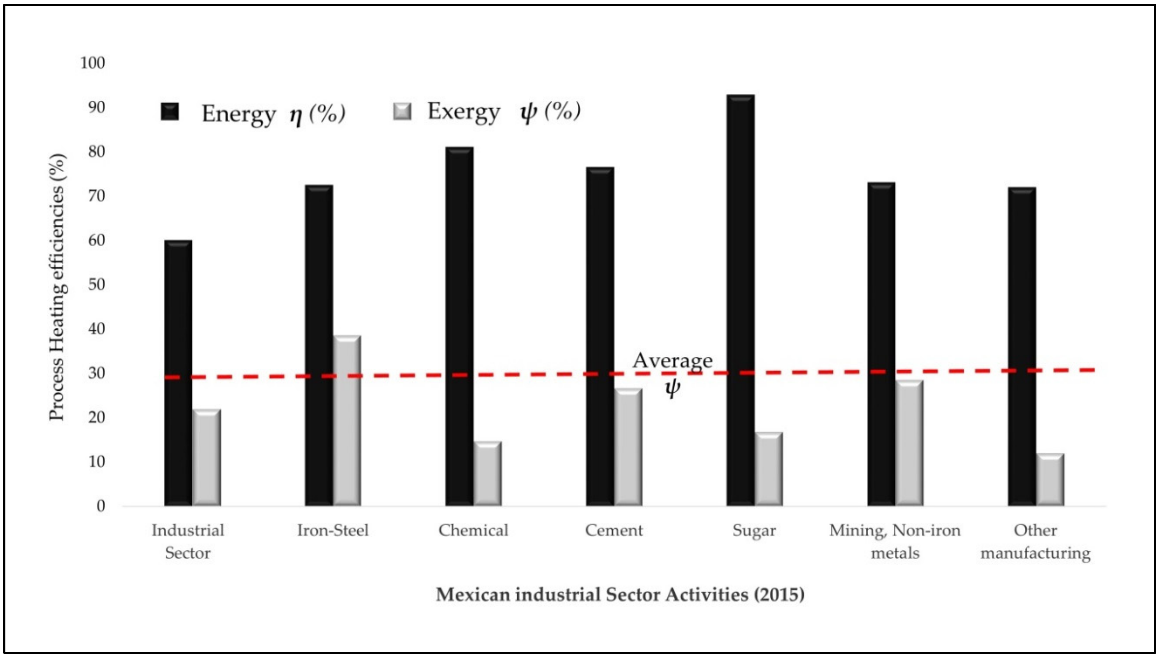

Figure 5-4 MIS average energetic and exergetic efficiencies,
industrial activity breakdown for the year 2015

Essentially, for the analyzed 16 years, the sugar industry seems to perform best based on its highest overall energy efficiency (70.9%) but its corresponding exergy-based performance is the lowest (17.4%), and its difference for improvement is the largest of the sector (49.7%). A similar analysis of the iron and steel subsector confirms the previous claim. During the analyzed 16 years, it seems to perform best based on overall energy efficiency (72.6%); its overall exergy-based performance is the highest (33.9%) of the MIS; and its difference for improvement is the lowest of the whole sector (12.9%). These exergy losses or irreversibility from manufacturing activities embody the true thermodynamic inefficiencies of the sector.

The main reason behind this behavior occurs because electricity (a high-grade source) is still commonly utilized in low-grade in the sugar, chemical and other manufacturing subsectors (García Kerdan et al., 2015; Gong & Wall, 2016). Regarding improvement areas based on energy and exergy analysis, effective energy diversification strategies are needed by the MIS to achieve greater exergy efficiencies. The core actions detected as needing to be developed and focused on are: regulations and standards; fiscal policies; agreements and targets;

reporting, benchmarking, and training programs; and technological improvements. These strategies have been successfully developed in other countries (Abdelaziz et al., 2011; R. Banerjee et al., 2012; Kondo, 2009).

5.5.4 Mexican Industrial Sector (MIS) exergetic renewable share (ERS) compute and comparison with overall exergy efficiencies

Figure 5-5, shows the comparison of renewable share and exergy efficiency. In accordance with Gong (Gong & Wall, 2016) the renewable share is expressed as a sustainability indicator of a system under study. Subsequently, once exergy efficiency and the exergetic renewable share were computed, we established two sets of analyses. First, the evolution of the MIS, through the complete span of study were computed (Table 5-4), then, exergetic renewable share and exergy efficiency by means of sustainability indicators were also computed.

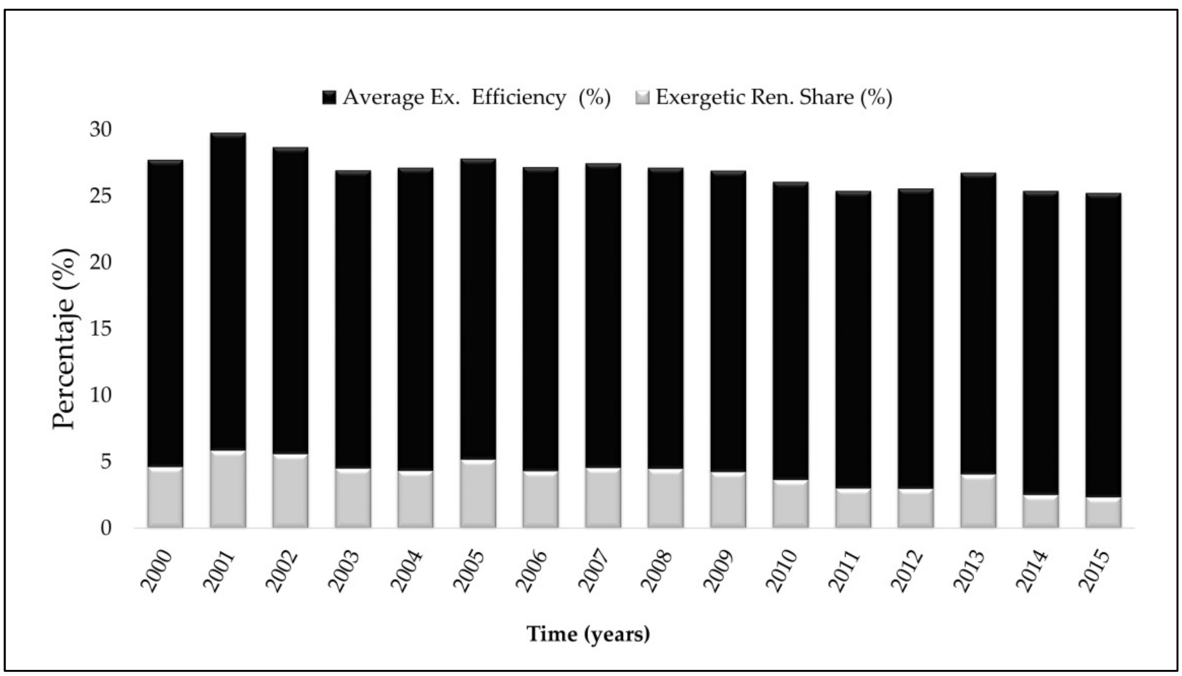

Figure 5-5 MIS evolution of exergy efficiencies and exergetic renewable share as sustainability indicators, 2000–2015

In regards to the MIS renewable exergy evolution, the rates tend to decrease during the 16-year span (about 38 PJ), with a lower mark by the year 2015, despite the fact that the sugar subsector increases its share of renewables. These results, to some extent, are linked with the semi-constant maturing of the Mexican economy. Since the year 2000, the energy demand in Mexico has grown by a quarter, and the electricity consumption has grown by half (International Energy Agency (IEA), 2016b). Regardless of almost constant values for exergy efficiency, however, the irregularity of the exergetic renewable share (with a maximum of 5.9% by year 2002, and a minimum of 2.4% by year 2015). For the whole period of study, the average computed values for the MIS were: 4.1% for exergetic renewable share and 22.8 % of exergy efficiency.

According to the IEA reports on future Mexican Policies Scenario (International Energy Agency (IEA), 2016b), electricity demand will remain one of the two main sources of energy. At the same time, to minimize the intensity of the use of fossil fuels, electricity demand in Mexico will grow at an average annual rate of 2.4% between 2014 and 2040 with a pace faster than the OECD average. Then, sustainable analysis and practices are mandatory for these future scenarios, considering the challenging dependence of fossil fuels in an oil producer country.

5.5.4.1 Mexican Industrial Sector (MIS) comparison of exergy efficiencies (ψ) and exergetic renewable share (RS) as sustainable indicators

A thorough literature review of previous studies was carried out to establish a comparison between MIS results and similar ones. The work by three main scholars, Ertesvåg, Utlu and Bligh (Bligh & Ugursal, 2012; Ertesvåg, 2001; Utlu & Hepbasli, 2007b) offers a total of 16 different countries, 21 different years and 41 data series within nearly 75 references, with an exergy efficiency average of 38.4% (Bligh & Ugursal, 2012; BoroumandJazi et al., 2013; Ertesvåg, 2001; M. A. Rosen, 1992; Enrico Sciubba et al., 2008; Göran Wall et al., 1994). To construct Figure 5-6, the main criterion was based off of the countries with bigger exergy efficiency values, including data from the OECD and the World with an average of 47.9% of exergy efficiency. Starting with IEA website databases (International Energy Agency (IEA), 2017b), we reviewed the energy balances by country, and obtained the values of Total Energy Inputs (total final consumption) and the values of renewable sources for the industrial sector consumption (hydro, geothermal, solar, biofuels & waste).

At first sight, the exergetic renewable share of three countries: Brazil, Finland and Sweden, are above average with respect to others. MIS results are the second lowest due a low share of renewables, above just Iran and the Netherlands. Equally important, comparing the exergy efficiencies of the MIS, the graphic shows that its results (22.9%) are a little farther from most of the results in this graphic. The closest are those of the World in 1990 (27%). It confirms that improvement areas, a vast amount of 14% to at least, reach the average mean value obtained (37 %), depicted in Figure 5-6.

This divergence may be related to different sources of energy and technological advances through time. Due to the different methodological approaches to collect and analyze data, in terms of exergy efficiencies, this comparison offers a valuable idea for the industrial sector, even when it is always a challenge to equate and contrast different societies around the world. According to Banerjee, the overall global exergy efficiency rate is only 30%, an indicator that persists numerous energy efficiencies improvement opportunities through research and development for next generation industrial processes (R. Banerjee et al., 2012).

Although this is a small sample of the industrial sector worldwide, the results of our study could be generalized to those high energy consume industrial activities. We are aware that the methods applied to previous exergy analyses of the industrial sectors and in our research may have limitations. In a strict physical sense, some societies seem more efficient than others, however, in a broader perspective, a country or a society cannot be simplified like this (Ertesvåg, 2001; Gong & Wall, 2016).

In addition, beyond the lack of availability of data from previous and actual flows for energy balances, renewable shares, exergy efficiencies and the years in which those studies were developed could influence the results. The more recent the analyses are performed, the more improvements in methodological steps there would be. Consequently, the greater the amount of renewable energy sources, the greater number of positive factors inducing societal exergy improvements we could obtain. Moreover, when analyses conducted in different periods of time are utilized to compare worldwide societies, then a certain degree of risk would remain.

5.5.4.2 Mexican Industrial Sector (MIS) comparison of exergy efficiencies (ψ) and exergetic renewable share (ERS) with other countries

To compute the country's ERS, we followed the same methodological steps used previously to compute MIS-RS with the IEA data sources (International Energy Agency (IEA), 2017b). It is noticeable that this data base offers only values from the year 1990 to the year 2015. Therefore, our approach takes values of the year 1990 as the minimal criteria for those countries with previous exergy efficiencies studies (Brazil 1987, Finland 1985, Canada 1986). Figure 5-6 display results for both indicators, with average ERS values of 13.7%, with the highest of 49.6% (Brazil) and the lowest of 0% (Iran, 2012). Similar values of both factors give Brazil the biggest results when comparing countries, contrasting with the Netherlands with the second-biggest exergy efficiency but with the second-lowest exergetic renewable share of 3%. It is interesting how Brazil has been increasing their exergetic renewable share since 1990s; based on a strong infrastructure to produce renewable fuels, supported by a positive value in their general energy balance.

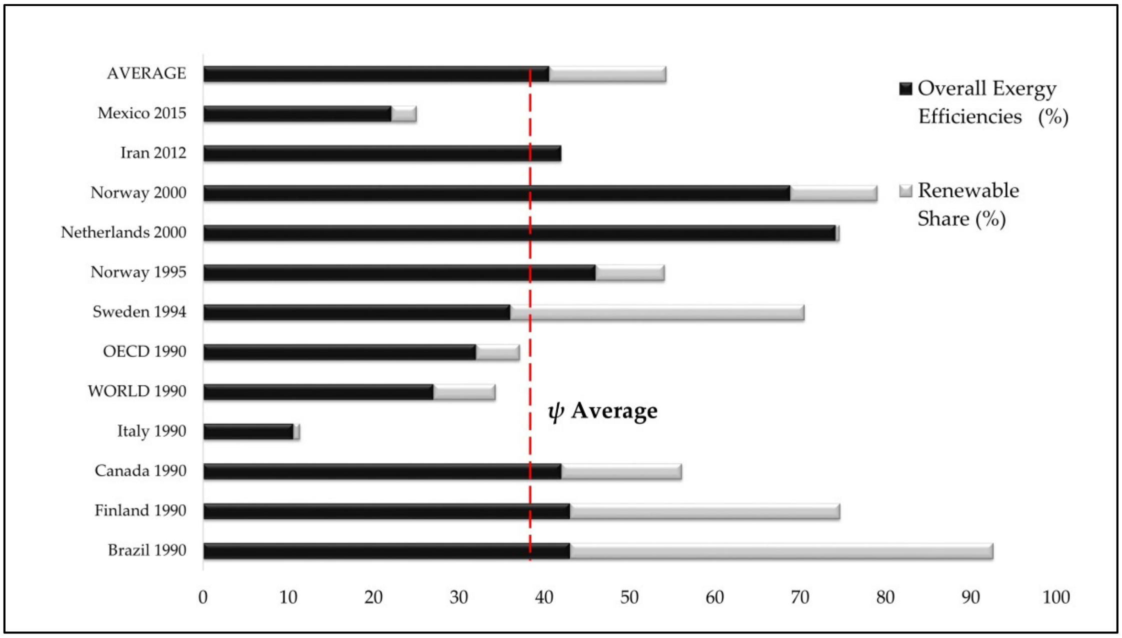

Figure 5-6 Comparison of countries exergy efficiencies and exergetic renewable share as sustainability indicators

The MIS-Exergetic renewable share value (2.9% in 2015) is considerably below average, mainly due to a poor level of exergetic renewable share (discussed previously in section 5.4.3). The graphic shows most of the values for the countries above average, including those of the OECD and World. Our study provides additional support for the sectorial exergy analysis methods, with the approach of exergetic renewable share and sustainability index to strengthen the interconnection of the exergy concept and environmental issues.

According to Koroneos (Koroneos et al., 2012) the development of exergetic indicators could be a useful tool for the location of energy degradation spots, energy conversion, environmental impact producing materials or giving an insight on technology substitutions. One of our goals in this paper was based on the approach that once exergy efficiency tends to increase, environmental impacts (air emissions) conversely decrease, and hereafter, sustainability will increase. Through the computation and comparison of the exergetic renewable share with exergy efficiency for our study case, we confirm that both indicators confirm this statement (Dincer & Rosen, 2004).

5.6 Conclusions

The main goal of the current research was to analyze the total final consumption of energy and exergy, as well as to compare the thermodynamic energy and exergy efficiencies of the industrial sector to detect improvement areas. The research was developed based on a study case in Mexico, from 2000 to 2015. Besides, the exergetic renewable share was analyzed. The following conclusions may be drawn from the results.

This paper has shown the need to bring it up-to-date the exergy analysis method applied to the industrial sector, for this reason process heating temperatures, electricity and fossil fuel efficiencies were modified. These changes influenced the compute of energy and exergy efficiencies, compared to previous studies, our results show a slight tendency to increase mainly on the energetic efficiencies.

The research has also shown that, since the exergy analysis is an extensive and systemic method that detects the maximum amount of work that a system can produce, it is a more suitable tool than energy balances to evaluate and improve the thermodynamic performance of the system. Our results display improvement areas. The comparisons of energy and exergy efficiencies point-out the need to increase exergy efficiencies, the following strategies are proposed: regulations-standard, fiscal policies, agreements-targets, reporting-benchmarking-training programs and technological improvements. It should allow for the MIS to take the sustainable path. The replicability of our research was confirmed when our results were compared with other countries.

The results of this research support the idea that exergy is different that energy. Scholars claim that it is important to employ exergy analysis to complement the prevailing energy-based methods utilized to develop official reports or environmental and energetic strategies. Thus, decision makers in society should consider not only apply the energy balances methods to write official reports or design future projects, it is necessary to reinforce them with the exergy analysis methodology, especially since it was demonstrated that exergy provides key elements to improve the energetic performance.

This study has gone some way towards enhancing our understanding of the current methods of sectorial exergy analysis; as a contribution to seal the gap between exergy and the environment theories, the renewable share coupled with the exergy efficiency were proposed as a new approach to boost sustainability. The results of the Mexican exergetic renewable share (ExRS), compared with other countries, unveiled the low fraction of the MIS. It is an indicator that continued efforts are needed to upgrade the ERS in a more sustainable path to increase the use of renewable fuels in the industrial sector, not only locally in the Mexican industry, but also globally.

Our approach could be useful for future research to analyze the industrial sector, particularly the emerging- market economies. Although it is a small study of sectorial societies, our results could be generalized to industrial activities with high energy consumption, contributing to decreasing the lack of similar studies. More broadly, research is also needed to develop the exergy analysis of the whole Mexican society, as well as the study of the interactions between the thermodynamic efficiency and other variables, i.e., social and economic, to continue in search of a more sustainable industrial sector.

CHAPTER 6

GENERAL DISCUSSION

6.1 Summary of research work

This section describes theoretical implications from the results and findings derived of the three articles (in the form of Chapter 3, Chapter 4 and Chapter 5). This thesis addressed the general problem of anthropogenic emissions of carbon dioxide (CO_2), from the use of fossil fuels as main source for industrial activities, whose fast-increasing rates to the atmosphere may be greater than the earth's ability to assimilate it. Currently levels of CO_2 (near 410 ppm) are higher than at any point in human history.

First, a novel approach was proposed, applying exergy analysis to study the role of exergy on Carbon dioxide emissions, energy consumption and economic growth, in the form of a comparative empirical study of ten countries (Chapter 3). Second, an empirical study was conducted to test the influence of economic, social and energy and exergy variables to determine the existence of the environmental Kuznets curve in NAFTA countries and their applicability on energy and environmental policies (Chapter 4). Finally, a study case was accomplished to compute the exergy indicators of the Mexican industrial sector (Chapter 5).

The main goal of this research was to validate the appropriateness of the exergy analysis, as a tool to assist decision makers in the design for future energy and environmental policy as an approach to enhance sustainable strategies. Accordingly, to detect the influence of socio-economic variables on environment, Chapter 4 includes the analysis of economic growth and trade openness. Similarly, in Chapter 5 were included economic growth, trade openness and the human development index as social variable. In Chapter 6, to contribute to the environmental dimension of sustainability, the renewable share of fuels was analyzed and proposed as an indicator.

Although the contributions of this thesis address independent problems, they are also complementary. In the following sections, we discuss them with a global perspective, focusing on their possible applications. The main contributions addressed in each chapter, are exergy indicators as a tool to assist the design for future energy and environmental policy.

6.1.1 Preliminary results regarding correlation among variables (EKC exploration)

The first stage of this research (Global level) was to study the correlations between CO_2 emissions and its drivers; a set of several variables including the three dimensions of sustainability were included. After the first statistical test, we detected that the most influential model to detect how correlated those variables are and which variable is determining CO_2 emissions, is the EKC theory. Consequently, the EKC methodology was explored.

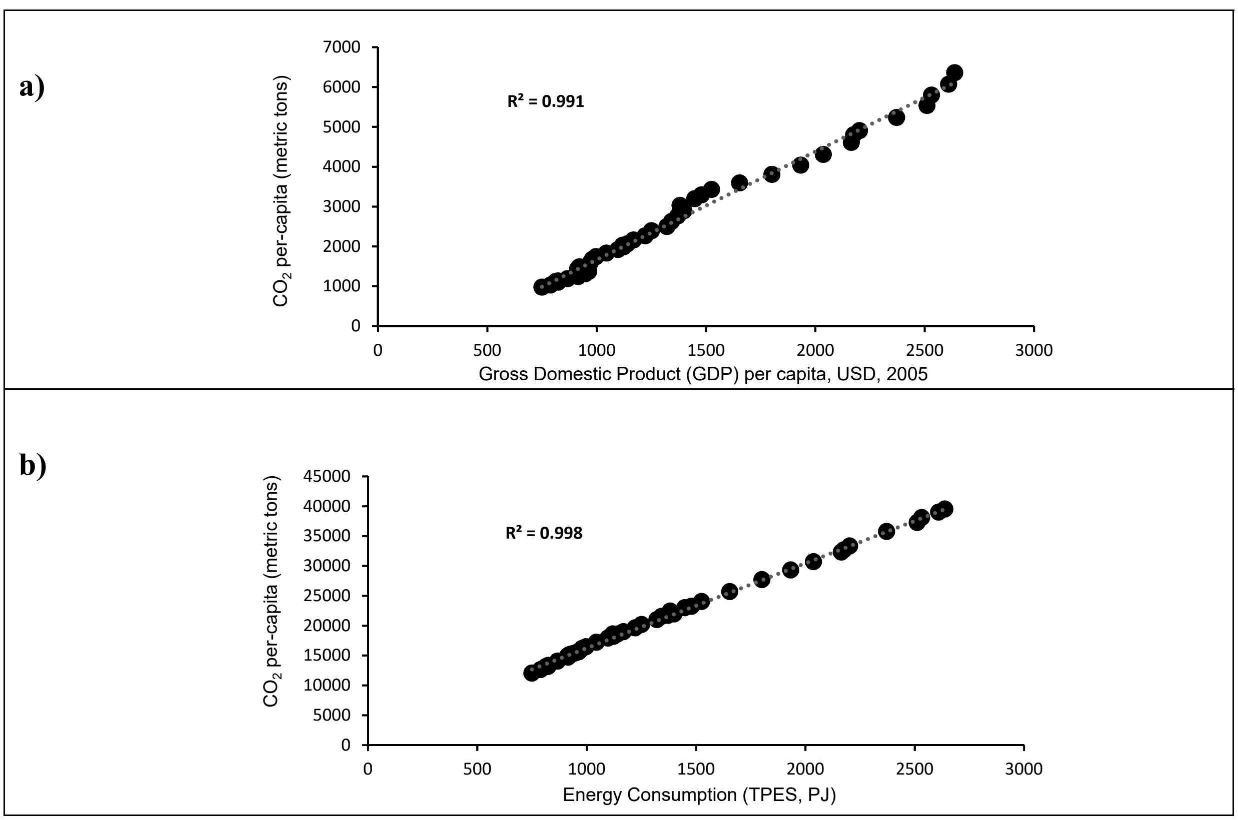

Figure 6-1 Global level correlation curves: a) GDP per capita vs CO_2 per capita emissions. b) Energy consumption vs CO_2 per capita emissions

Fig. 6-1 Shows correlations among the three main variables tested in the search of the environmental Kuznets curve (EKC), those are: energy consumption, gross domestic product (GDP) and CO_2 emissions. Despite strong correlations were detected between GDP and CO_2, energy consumption and CO_2 and exergy consumption and CO_2, however, the EKC was not confirmed.

This figure also describes the correlation curves between the two most correlated variables of CO_2 emissions: GDPs per capita and exergy consumption. An increase in GDP pc is associated with an increase in the level of emissions per person. However, the correlation pattern between the two variables ceases to be linear when the GDP per capita value exceeds 1500 USD. From this point a slower decrease trend is showed, which point to confirm the Kuznets hypothesis, after a turning point GDP will increase but the CO_2 emissions will decrease. This is similar with previous reports, referred in Chapter 1, Table 6-1. It was interesting to observe that the possibility to find the EKC exist in the set of ten countries, despite been a great panel of countries, it opens the door to going deeper in search of the EKC, which was the focus of the Chapter No. 5.of this thesis. Fig. 6-1 b) shows strong correlation but no sign of decrease. As it was showed in Fig. 6-1. a), in the long run the behavior of both parameters as control variables depicts a growing linear trend, not a Kuznets curve reinforcing the need to develop a new analysis with a lesser amount of countries and smaller period, with stronger statistical methods.

The second stage of this research (Regional level) was also to study the correlations between CO_2 emissions and its drivers; a similar set of several variables was included. The major difference with the previous stage was to apply econometric methods to determine the existence or not of the EKC. Results of this part will be showed in the following section, 6.1.2. Meanwhile, Figure 6-2 below shows the results of the correlations among the more influential variables of CO_2 emissions.

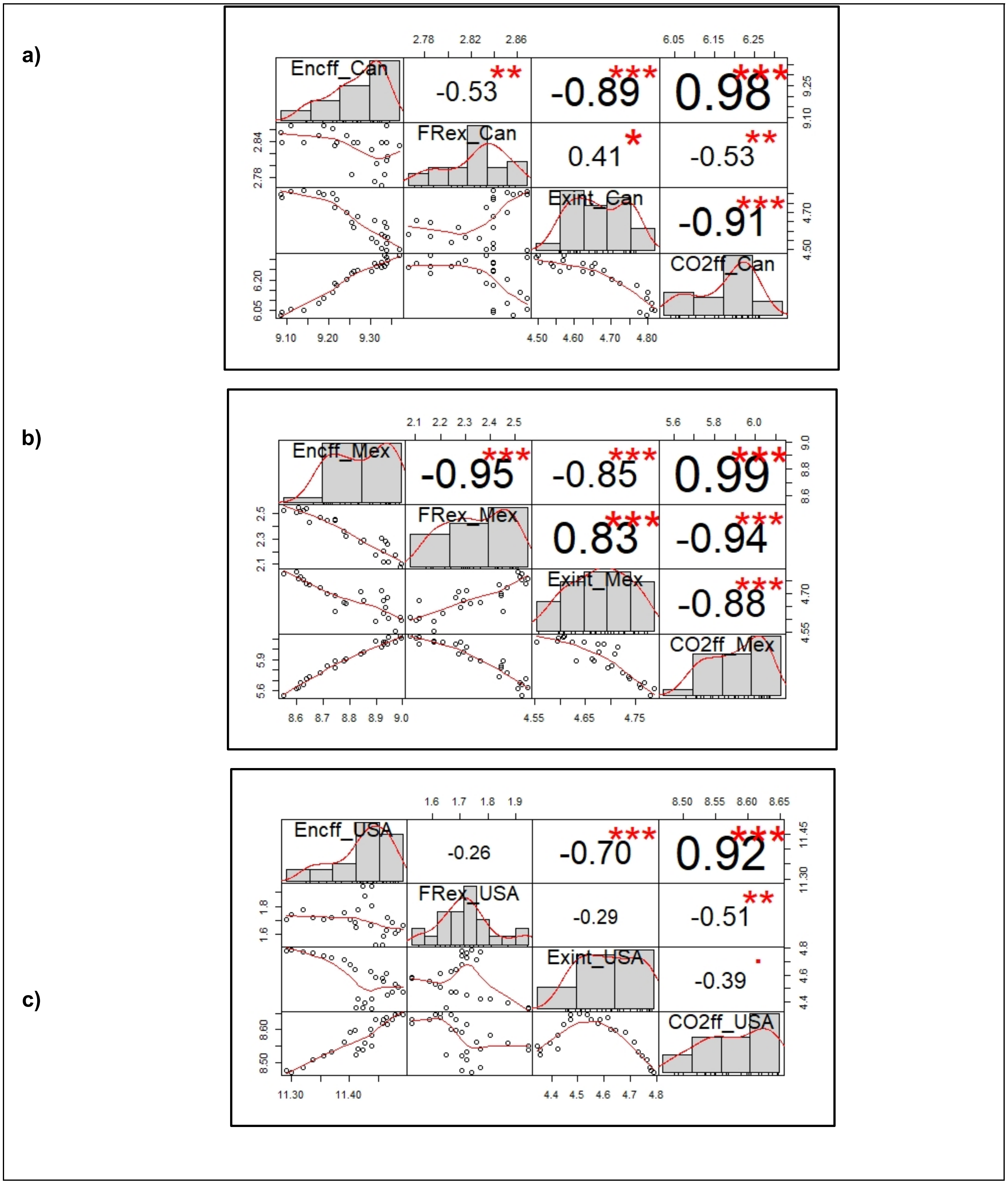

Figure 6-2 Regional level correlation curves: a) GDP per capita vs CO_2 per capita Emissions; b) Energy consumption vs CO_2 per capita emissions

In Figure 6-2 a), we observe the results for Canada, highlighting strong correlations between CO_2 emissions vs energy consumption, CO_2 emissions vs exergy consumption. Figure 6-2 b), show similar results, between CO_2 emissions vs energy consumption., CO_2 emissions vs exergy consumption and CO_2 emissions vs exergy renewable share are strongly correlated to Mexico. Lastly, Figure 6-2 c) describes different correlations for the USA the stronger correlation detected was between CO_2 emissions vs energy consumption.

It is important to remark that in the third stage of this research (Local level) were determined strong correlations between CO_2 emissions, GDP per capita and energy consumption, but the Kuznets curve was not observed, a deeper discussion will be described in the following section.

6.1.2 Results appiying the EKC methods

To continue the analysis at global level, Figure 6-3 below show scatter diagrams (logarithmic values) for CO_2 emissions plotted versus the most influential control variables. Some of them allow observing a positive trend, although with a decreasing step, what makes us suspect the possible existence of the EKC.. A multi-variable framework, described in Chapter 3, was applied to examine relationships between CO_2 emissions, energy consumption and economic growth.

a)

b)

c)

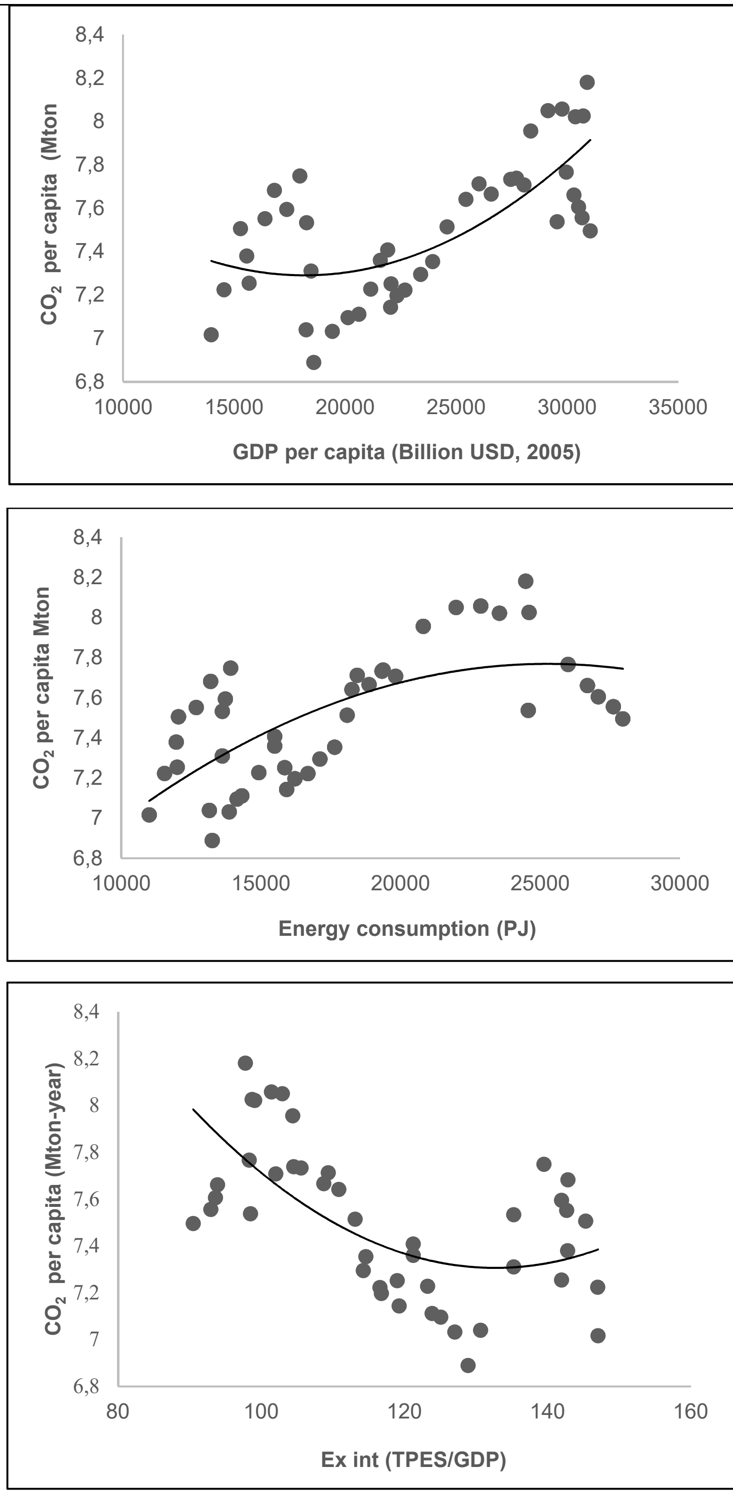

Figure 6-3 Global level Kuznets curve: a) GDP per capita vs CO_2 per capita; b) Energy consumption vs CO_2 per capita; c) Exergy intensity vs CO_2 per capita

In the short run, 6.2 a) describes a growing trend of CO_2 per capita, concurrently with GDP per capita. Consequently the first part of the curve is validated, once an increase in economic growth outcomes the growth of CO_2, resulting in pollution increasing. The value of $R^2 = 0.99$ infers that in a second stage, when the GDP pc remains increasing, also the CO_2 emissions will increase, non-validating the second part of the EKC curve. One influential factor is the diversity on the selected set of countries, including a mix of developed and -developing countries, with diversity of GDP and energy consumption. These findings are similar to previous research, once the developed countries have shown evidence of the EKC, contrary to the developing countries (Ahmed, 2017; Ertugrul, Cetin, Seker, & Dogan, 2016).

Figures 6-3 b) and c), displays diagrams for energy and exergy variables. Firstly, in Fig. 6.3 b) we can observe a similar behaviour than in the curve of Figure 6-2 a), suggesting and inverted U curve or even an inverted N shape curve; however, evidence in the existence of the EKC is valid only for developed countries and not in the developing group. Similar results are reported by Chontanawat (Chontanawat et al., 2008). Developed countries report growth or feedback hypothesis (Lee et al., 2008), while, in developing economies like China, only the growth hypothesis is suggested (X.-P. Zhang & Cheng, 2009).

Particularly, figure 6-3 c) depicts an inverted N shape curve, and then no growth or feedback hypothesis was found. The correlation is low, and the increase-decrease-increase tendencies of the curve suggest even a double inverted U curve. But, in the long run, the curve decreases due its negative correlation coefficient (R^2 = -0.99). Despite this negative trend, the exergy intensity remains as an interesting control variable due the high correlation.. Even though most of the statistically significant results show an N-shaped EKC, the results achieved are heterogeneous, then the EKC hypothesis was not supported. Further breakdowns of the countries are recommended to help explain the relationship between these variables (Allard, Takman, Uddin, & Ahmed, 2018).

As stated previously, at regional level (Chapter No. 4) the sample was reduced to a subset of countries (Canada, Mexico and the USA) and the period of study was shortened. In addition, two more statistical (econometric) tests were added named VAR (vector analytic regression) and Granger causality to determine the existence or not of the EKC hypothesis.

Below, Figure 6-4 describes the results in the search of the EKC; only two graphic results confirmed the EKC of the USA, neither for Canada nor Mexico.

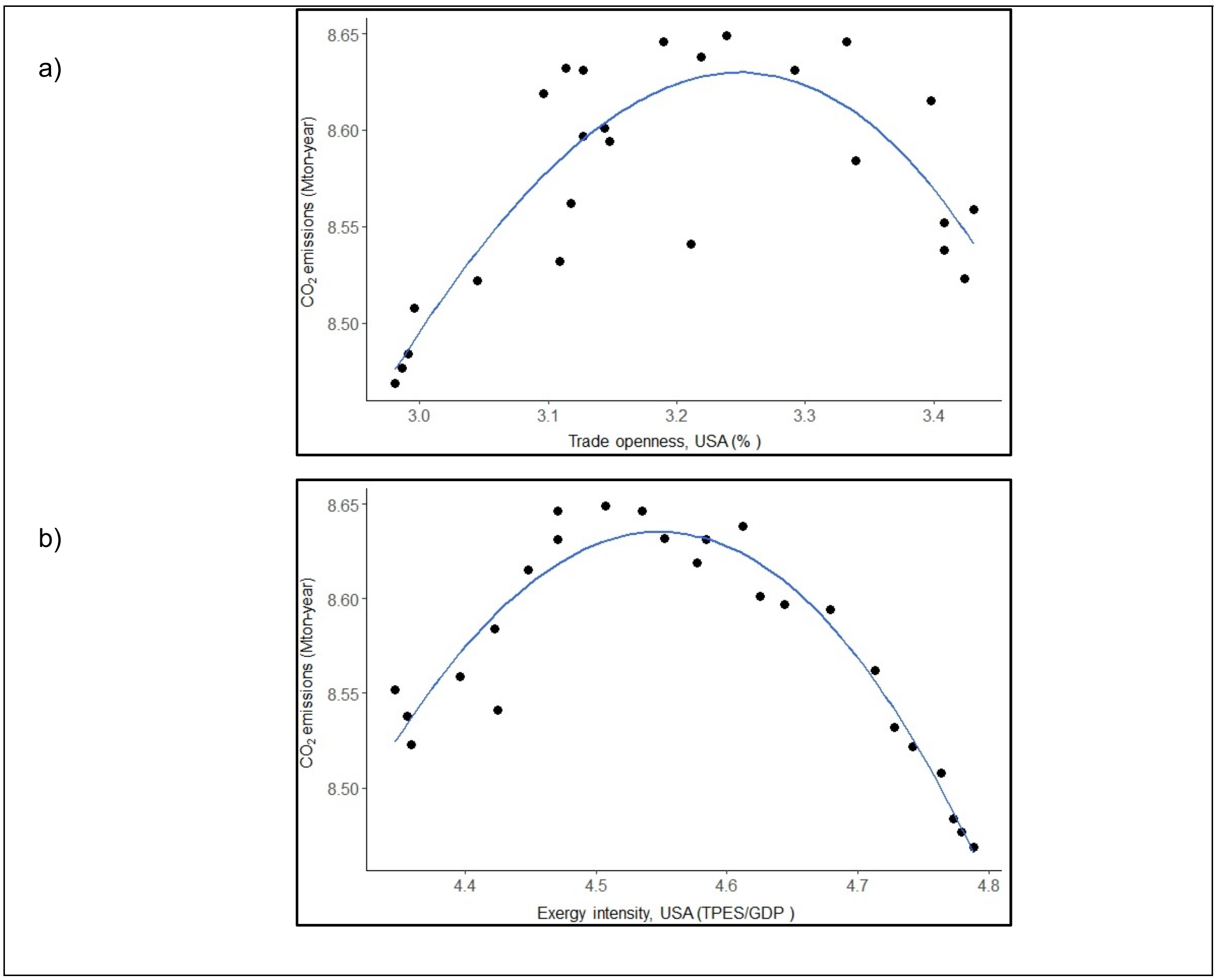

Figure 6-4 Regional level Kuznets curve (the USA). a) Trade openness vs CO_2 per capita. b) Exergy intensity vs CO_2 per capita

The non-confirmed EKC outcome of our research are similar to those of previous research regarding Canada (He & Richard, 2010), Mexico (Gómez et al., 2018) and the USA (Dogan

& Turkekul, 2016b). The more interesting result was to find the EKC for the exergy intensity as well for trade openness.

Regarding the Granger causal results, trade openness causes CO_2 emissions by Canada and the USA; in 2016 Dogan (Dogan & Turkekul, 2016a), reported similar results: trade openness is a determinant of carbon emissions in the long run by the USA.

At local level (Chapter 5) a case study was developed; the sample was the industrial sector of Mexico and the period of study was also shortened. Using Pearson correlation, it was found that all variables are integrated of order 1.

We did not went further testing the existence of the EKC once the previous the two previous chapters of the thesis do not show insights in the case of Mexico. As Figure 6-5 a), b) and c) reveals, the EKC was not confirmed.

Also, Figure 6-5 describes high correlations among energy intensity vs CO_2 per capita; energy consumption vs CO_2 per capita; and CO_2 per capita vs GDP per capita. The variables are highly correlated in the short and long run

As stated in the methods section, after the EKC do not give results to propose policy at local level, instead, we computed energy and exergy efficiencies to complement this third stage of the research. In the following section, the discussion of these results will take place.

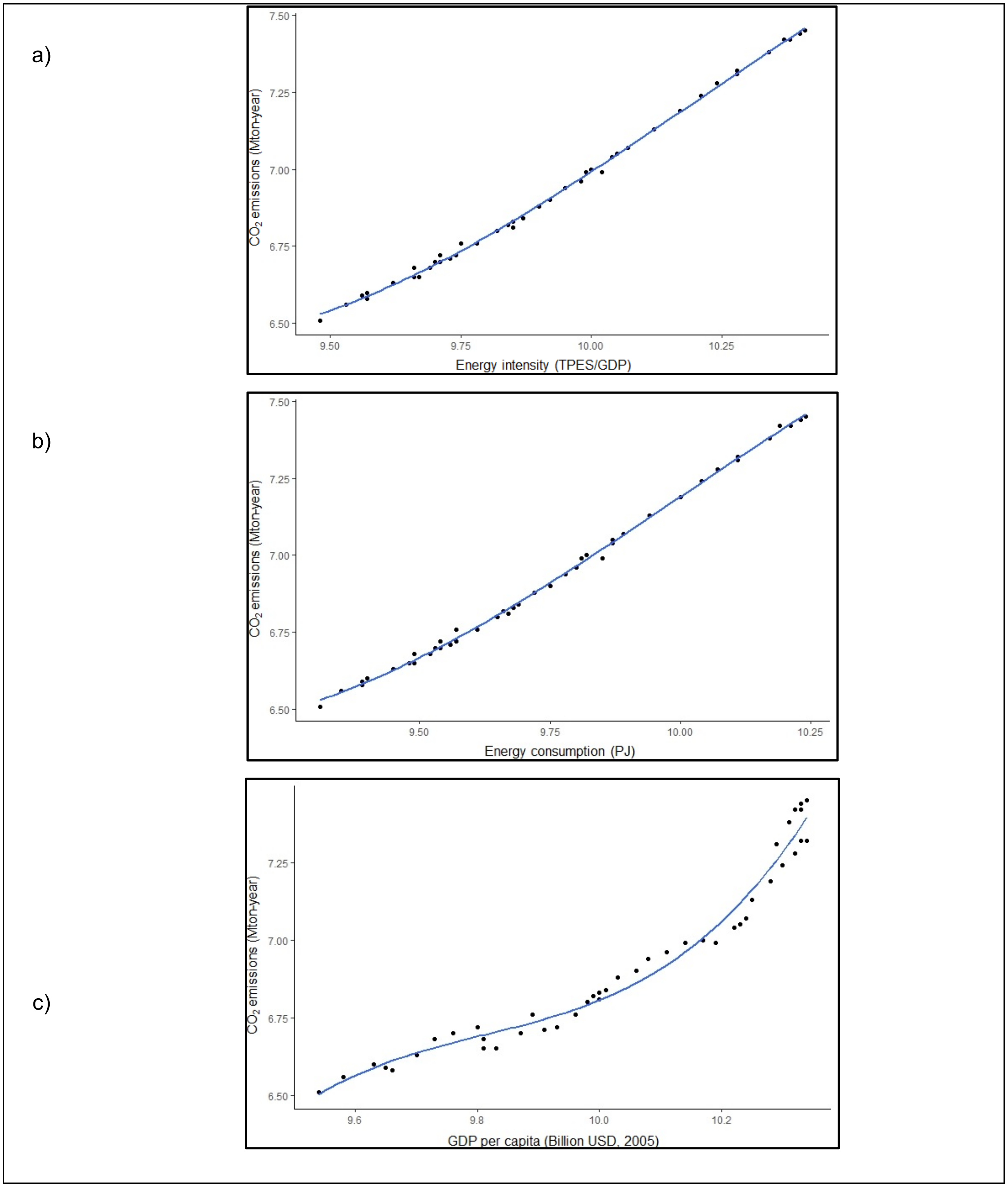

Figure 6-5 Local level Kuznets curve (Mexico): a) Energy intensity vs CO_2 per capita.
b) Energy consumption vs CO_2 per capita
c) GDP per capita vs CO_2 per capita

Despite the considerably amount of empirical evidence, controversy still surrounding the EKC hypothesis. Detractors consider the main issue consists of, how the income-pollution relationship evolves when the EKC hypothesis ceases to be valid, mainly comparing developed and developing economies? Previous research shows that developing countries are expected to behave differently than developed countries since socio-economic and politic unique conditions change over time (Kaika & Zervas, 2013b).

Consequently, economic policy makers need to be careful promoting economic growth and simultaneously hoping to reduce environmental degradation ; they need to keep in mind they are evaluating only two key dimensions of sustainability, the economy and the environment (Alam et al., 2016) in a quite range of multi variable effects. According with Stern the complexity of econometric models, convergence and time effects should get more attention for future studies (David I. Stern, 2017). Furthermore, a question arises, it is possible that developing countries reach a point of decline in the Kuznets curve without going through a maximum peak, thus accelerating the decrease in CO_2 emissions? Future research is proposed.

6.1.3 Suitability of energy-exergy and environmental variables

Regarding the suitability of exergy tools in the design of energy and environmental policies in an effort to enhance sustainable strategies, at global level (Chapter 3) was proposed CO_2 emissions from fossil fuels as environmental degradation variable. As drivers of CO_2 emissions, the following variables were included: energy consumption from fossil fuels, energy intensity, carbon intensity, exergy consumption and exergy intensity. Similarly, in at regional level (Chapter 4) CO_2 emissions was considered as environmental degradation variable; as drivers of CO_2 emissions, the variables included were energy consumption, exergy intensity and exergetic renewable share.

Comparing with similar results from other countries, the results of two exergy variables of the Mexican industrial sector (MIS), exergy efficiency and the exergetic renewable share (ExRS), revealed low scores. It is an indicator that continued efforts are needed to improve

exergy efficiency and the ExRS. A path to follow can be to increase the use of renewable fuels in the industrial sector, particularly on the non-extensive energy activities.
Similar to previous research (Gong & Wall, 2016) in Chapter 4 the ExRS was also computed for the MIS as well for the other countries. With these insights, a better understanding is obtained of that the factors affecting efficiency, and efforts to improve performance can be better allocated and directed .

Concerning the implications for energy policy to reduce energy consumption without affecting production, our findings suggest that other energy policies should be explored, i.e. those related to reducing energy intensity, promote the generation and consumption of cleaner energy based in the use of exergy indicators and the increase in the renewable share (Gómez & Rodríguez, 2016; Valenzuela & Qi, 2012).

6.1.4 Limitations and uncertainty of the results

In the methods section of Chapter 2, a matrix dataset including several variables and ten countries was proposed to be the main structure linking the three main parts of this thesis. The International energy agency website was the key source, complemented with other databases or official reports.

The common problem in research was faced here, since one of the main limitations to this study was the availability of the data, mainly in years prior to 1970's, particularly for developing countries. Another big question arises from the analysis of the databases. We detect that most available data is older than two years. Hence, to achieve the main goal of this thesis which consists to validate exergy tools in the design of future energy and environmental policies, we need newer data to propose real- time policies and so be able to improve socioeconomic systems in a proper way. Another question arises: how to get reliable data to apply exergy tools in the task to help decision makers to enhance politics and regulations? We propose to apply current information technology advantages (gadgets, applications, cloud computing, etc.) to construct newer and ad-hoc datasets to solve problems, facility level, corporation level and more.

The compute of exergy efficiency of the Mexican industrial sector was developed in Chapter 5 and results were compared with previous works. Due to the different methodological approaches to collect and analyze data, in terms of exergy efficiencies, this comparison offers a valuable idea for the industrial sector; however, the comparison of different societies, it is always a challenge; some limitations arise to equate and contrast the study of these large-scale systems(M. Rosen & Bulucea, 2009).

According with Romero (Romero & Linares, 2014), although using exergy means a step forward in the way of dealing with global sustainability concerns, it is fair to acknowledge that it is barely capable of dealing with some dimensions of sustainability related to social issues, i.e. equity and wealth allocation, a limitation inherent to all the thermo-economic proposals. Hence, the contribution of exergy to sustainability assessments is normally restricted to the environmental pole. In this work some exergy indicators were applied, exergy consumption, exergy intensity and renewable exergetic share as a contribution to the assessment tools of the above-mentioned bio-physical category of sustainability.

6.2 Operational implications of exergetic indicators

This thesis work based on an empirical research results suggest some evidence–based implications regarding Carbon dioxide emissions and gross domestic product tests in the search for the EKC, with the goal to propose tolls to minimize negative effects of CO_2 emissions and so ease the path to sustainable societies.

The main goal of this thesis was to validate the pertinence of exergy in the design of energy-environmental policies and at the same time contributing to the environmental dimension of sustainability. Accordingly, one of the most remarkable result to emerge from the data is that, as mentioned by Gaudreau (Gaudreau, Fraser, & Murphy, 2009), it is possible to apply exergy analysis as a decision-making tool with the goal to improve process efficiency as measured (via work or work potential); it is also possible to recognize areas of exergy destruction or entropy production (Gaudreau et al., 2009).

In accordance with the general and the three particular objectives of this research, on the relevance of the exergy indicators, Table 6-1 shows proposed strategies and potential policy proposals at the public and private level, as well as exercise indicators to support these initiatives.

Table 6-1 Proposed energy and environmental policy strategies by geographic approach

Problematic	Key Parameter	Potential policy and exergy indicator
Global geographic level		
Lack of results to achieve global targets on GHG's	Energy consumption, Economic growth CO_2, emissions Exergy intensity	Comprehensive codes and commitments to increase renewable share to reduce CO_2. Public policy**. Exergy intensity**
The energy consumption in urban region will increase rapidly in the future		Energy-saving and emissions- reducing policy should be carried out not only in the production field, but also in daily lives. Important societal role to increase sustainable consumption of goods and services. Public policy. **Exergy intensity**
Regional geographic level		
Relevant trade agreements open regional development opportunities	Trade openness	Stronger trade agreements, enhancing environmental chapters. Public policy. **Exergetic renewable share.**
inequality between rich and poor countries	Human development index	Socio-economic policy to reduce poverty. Public policy. **Exergetic renewable share.**
Local geographic level		
increasing renewable sources to decrease energy intensity by country	Energy consumption	Newer-cleaner energy generation models for developing countries. Private or corporate policy. **Exergy efficiency.**
The need of simpler applications to help small business, young practitioners.	Economic growth	Every person can use energy-saving devices and economize household energy to mitigate climate change. Private or corporate policy**. Exergy efficiency**.

Furthermore, it is necessary to increase the contribution of exergy analysis to the environmental field, consequently to sustainability. It is important for practitioners and policy makers to employ exergy analysis as a complement to the existing methods to develop datasets, official reports and environmental and energetic strategies (Arango-Miranda et al., 2018a).

Our study provides additional support for considerable insight into the development of exergetic indicators constitute a useful tool that can give insight for engineers to understand complex energy systems, some examples are to detect losses in condensers, combustion chambers or heat exchangers and so increase the exergetic improvement potential (Hammond & Stapleton, 2001; Koroneos et al., 2012). Other specific examples are:

- Degree of quality levels of energy supply and demand are matched
- Location and magnitude of energy degradation spots, resulting from heat transfer or energy conversion
- Environmental impact of producing, reusing and recycling building materials.

6.3 Future venues of research

How to tackle rate of Carbon dioxide emissions to the atmosphere to a sustainable or equal level to give the earth's the ability to assimilate it, remains as an open question. Knowledge about environmental tools to help to control, mitigation and gradually reduction of greenhouse emissions are needed. Globally, the goals to achieve it are already established and countries are committed to combat pollutant gases and their effects in the form of climate change.

As a practical application of this research work, we have shown that exergy analysis is a tool to minimize environmental damage. Consequently, future venues of research could be based on the application of complementary approaches, applying methodologies of dynamic models. In addition, it was demonstrated in results the relevance of the use of renewable sources of energy, and then the study of exergetic renewable indicators is recommended.

Chapters 3 and 4 presented the application of statistical and econometric methods; the study of newer, deeper statistical and econometric methodologies to explore the influence of GDP, energy and other key variables in CO_2 emissions, i.e., at country level or studying more societal sectors, is advised for future research venues.

As shown in Chapter 5, exergy analysis remains a hard task to achieve due the inherent complexity, even for practitioners, accordingly, future research could be based to develop, handbooks, guidelines and databases in the form of computational software or other technological applications tools available for practitioners.

Mexico is an important exporter of sugar, then, regarding technological applications, a particular study to improve the energetic performance of the Sugar industries can be developed. Once it was proved that the energy quality of this sector is currently low, it could be enhanced with exergy tools like the compute of the exergetic performance coefficient, by applying some technological modifications, i.e. super-heating or sub-cooling in the heat exchangers.

CONCLUSIONS

Carbon dioxide (CO_2) occurs naturally in Earth's atmosphere, presented as a trace gas. However, there is evidence that the rate of release of CO_2 to the atmosphere may be greater than the earth's ability to assimilate it. Modern societies require huge amounts of products and services, the consumption rates are constantly increasing, putting pressure on natural resource consumption, with undesired decline in forest and agricultural lands, solid waste generation, pollution of water basins and air pollutants. Due to constant growing consumption trends, societies increase the pressure on the industry to satisfy such demands. Globally, the industrial sector remains as one of the main consumers of energy, mostly from fossil fuels, particularly the heavy industry. In some industrialized countries, the rates of CO_2 emissions accounts for 79% of the total greenhouse gases (GHG) emissions. Many of these problems are directly or indirectly associated with the lack of proper environmental policies and regulations, or even deficient planning or a combination of both factors.

The main objective of this work was to validate the suitability of an environmental accounting method belonging to the energy analysis approach, the exergy analysis, to assist energy and environmental practitioners and research efforts for future policies and regulations at governmental institutions and private firms as well as their planning. In terms of sustainability, the exergy method allows the incorporation of socio-economic and environmental variables as drivers of CO_2 emissions.

This study applied a geographical level approach, going from global regional to local 9in the form of a study case). Panel data from the years 1971 to 2014 for ten countries were analyzed in a comparative empirical study of selected developed and developing countries. A main data set of 44 years including 10 countries served as a platform for the whole research of Chapters 3, 4 and 5. However, for the sake of the methods applied it was shortened in a subset of 3 countries and in the final stage into a single country (study case). Correspondingly, the time scale was also shortened level by level.

It was expected that economic growth, exergetic renewable share, trade openness and human development index could affect CO_2 emissions; even if it only were to a certain extent. In general terms it was validated the use of this the exergy methods with a different approach, has a promising potential as a tool for practitioners in future energy and environmental policies and regulations as an approach to enhance sustainable strategies

In Chapter 3, a strong correlation between CO_2, economic growth, energy consumption, energy intensity and trade openness was observed, on the other hand, not statistically significant values for trade openness and energy intensity. Despite the results do not support the EKC hypothesis, however exergy intensity opens the door for future research once it proves to be an interesting control variable. Finally, exergy provides opportunities to analyze and implement energy and environmental policies in these countries, with the possibility to link exergy efficiency and the use of renewables.

Chapter 4 describes the Environmental Kuznets curve (EKC) test for the North American region countries, including Canada, Mexico and the USA. The EKC hypothesis was not confirmed in the three countries. It was interesting to found Granger causality in Mexico and the USA, but not in Canada despite huge water resources and an interesting mix of hydro to produce electricity. In terms of Granger causalities, the results for Mexico and the USA are similar, but more insight was found in the USA. Contrarily, in Canada just one unidirectional causality was described, running from trade openness to CO_2 emissions. Trade openness was confirmed as driver of CO_2 emissions by Canada and the USA.

Interesting was to observe the results at local level of the study case of the Mexican industrial sector (Chapter 5). They showed the need to increase the exergetic efficiency and the exergetic improvement potential. This highlights the possibility of including multiple sectors and types of collaborators (scientific, practitioners and policy-maker communities) to design more comprehensive portfolios to combat greenhouse gases and global warming. Consequently, enhance climate change mitigation strategies. As a final point, the exergy efficiencies describe the efficiency of systems better, offering meaningful information. With these insights, a better understanding is made of the factors distressing efficiency, and efforts to improve performance can be better assigned and engaged.

To conclude this section, one final sentence summarizing and replying to the main objective of this work. The results validate the suitability of the exergy analysis to assist in the design for future energy and environmental policy, both in public and private institutions as an approach to enhance sustainable strategies.

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